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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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STRATIGRAPHY OF THE ONONDAGA LIMESTONE IN EASTERN NEW YORK

BY WILLIAM A. OLIVER, JR.

ABSTRACT

Four members of the Onondaga formation previously recognized in central New York are, in ascending order, the Edgecliff, Nedrow, Moorehouse, and Seneca limestones. In Onondaga County, the type area, each of these members is divisible into two or more zones, which are more or less continuous as far east as the Sangerfield quadrangle. Eastward the zones gradually become indistinct, and horizontal facies changes are of greater interest.

East of Cherry Valley the Seneca member grades laterally into the Union Springs black shale, which overlies the Onondaga formation.

The Nedrow member is well defined as far southwest as Kingston. Equivalent beds farther south are referred to the lower Moorehouse member, which rests directly on the Edgecliff. The Moorehouse and Edgecliff members are recognizable, although greatly changed, as far southeast as Port Jervis.

The lower Edgecliff grades into the Schoharie formation in southeastern New York and is probably represented by pre-Onondaga formations in northeastern Pennsylvania. The Buttermilk Falls limestone of eastern Pennsylvania is equated in time with the Moorehouse member of southeastern New York and the Nedrow and Moorehouse members of central and eastern New York.

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Introduction

The area covered in Oliver's (1954) discussion of the Onondaga limestone in central New York and the eastern and southeastern areas covered in this report are indicated in Figure 1. The division of the New York outcrop belt into four study areas is arbitrary, but is partly based on breaks in the continuity of outcrops and on facies changes. The 1954 paper included a summary of reconnaissance work in the eastern area, but involved no detailed study east of Richfield Springs.

The writer spent most of the summer of 1952 in the eastern area, and during the summer of 1953 was employed by the New York State Science Service to continue the work in eastern New York. Six weeks were spent collecting fossils and tracing units from Richfield Springs east to the Helderberg area, and 3 weeks were spent collecting fossils south to Kingston and southwest to Port Jervis (Fig. 2).

Exposures as far east and south as Kingston (Rosendale quad.) give a reasonably complete picture of Onondaga stratigraphy, but between Kingston and Port Jervis scattered small exposures give only a generalized picture.

Acknowledgments

The writer is indebted to Dr. Winifred Goldring, former New York State Paleontologist, and Dr. John Broughton, State Geologist, for the financial assistance and encouragement which made this work possible. Other geologists of the New York Geological Survey provided much data of value.

Previous Work

A critical review of the nomenclatorial history of the Onondaga limestone and of previous work was included in an earlier paper (Oliver, 1954). A considerable volume of literature exists on the areal geology and stratigraphy of the area under consideration. For the most part the Onondaga formation has been treated as a single stratigraphic unit, and fossil lists have generally been for the whole formation, commonly over a wide area. Several limited stratigraphic studies which have been made contribute greatly to this paper.

Thickness

In only a few places in eastern New York can the thickness of the Onondaga formation be accurately measured. Exposures of the complete formation are nonexistent. The upper and lower contacts crop out in the same ravine in a few places, but covered intervals and low, irregular dips make thickness measurements inaccurate. Scattered well sections give the most reliable figures.

Just west of the area under consideration, Prosser (1893, p. 96) reported 93 feet of Onondaga in the Morrisville well (Morrisville quad.). This thickness checks well with the author's measurement of 85+ feet at Stockbridge Falls in the same quadrangle. A general thickening eastward from this locality is evident.

Forty-five miles east of Stockbridge Falls, 0.8 mile south of Cherry Valley, a thickness of 118 feet was cored by the State College of Ceramics (Alfred). The core was studied by the author, and unit thicknesses are shown on Figure 3.

Twenty-eight miles farther east, 1 mile south of Gallupville, Berne quadrangle, a minimum thickness of 110 feet was measured. The upper contact is not exposed at this locality.

The Helderberg area (Berne-Albany quads.), 12 miles east of the above, is a classic paleontologic and stratigraphic area. Most workers have indicated the thickness of Onondaga in this area as approximately 100 feet (Prosser, 1900, p. 53; Goldring, 1935, p. 143). The College of Ceramics cored the Onondaga in Onesquethaw Creek (Albany quad.) and measured a thickness of 112 feet (R. Digman, Personal communication). According to Digman, however, the basal contact was doubtful so this may be a minimum figure.

South of the Helderbergs measurements of Onondaga thickness are uncertain. Chadwick (1944, p. 94) reported 60 feet in the Catskill quadrangle, although he was quoted by Goldring (1943, p. 227), as indicating 80 feet for the same area. However, in the Leeds gorge, just northwest of Catskill in the Coxsackie quadrangle, 115 feet is exposed, with the upper part of the formation covered.

Farther south, in the Kingston area, Darton (1894, p. 491) gave a thickness of 60 feet, and Van Ingen and Clarke (1903, p. 1205), 75 feet.

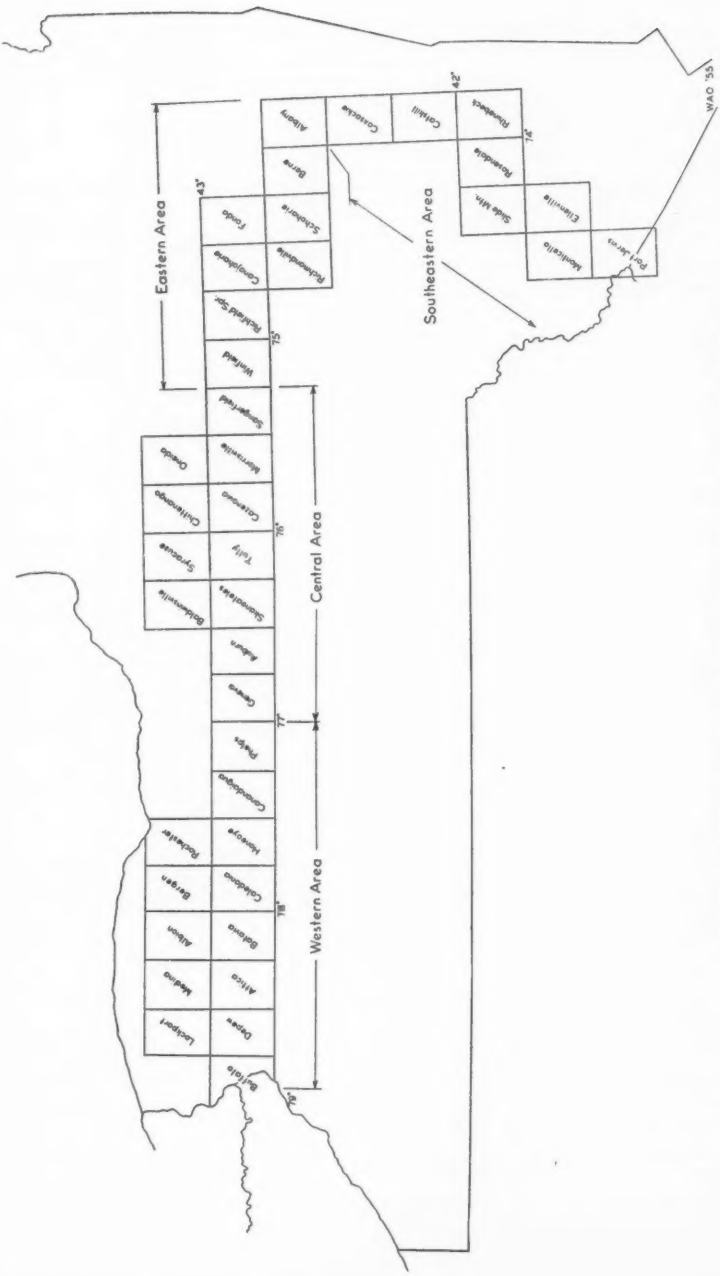

FIGURE 1.—INDEX MAP OF 15-MINUTE QUADRANGLES AND STUDY AREAS

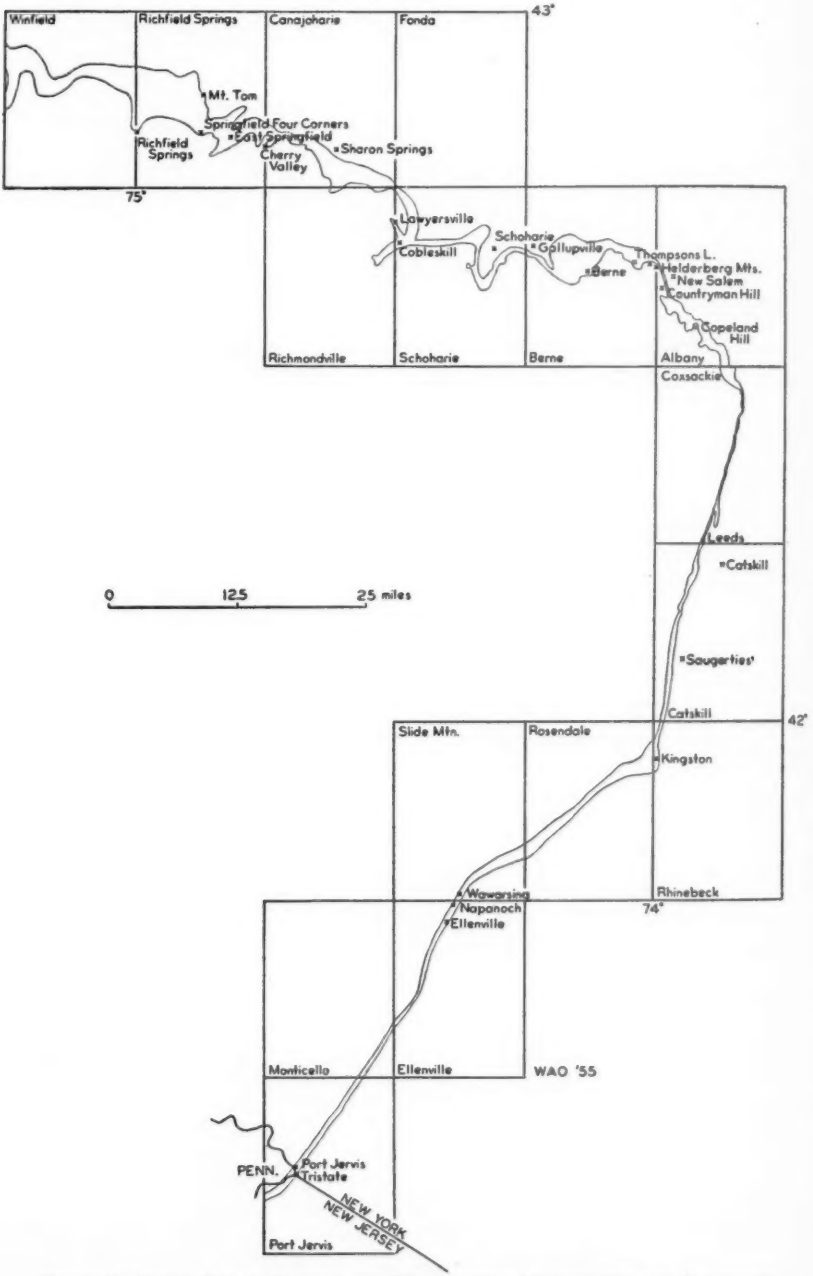

FIGURE 2.—INDEX MAP OF EASTERN AND SOUTHEASTERN QUADRANGLES AND LOCALITIES
Onondaga outcrop from published maps and additional field data

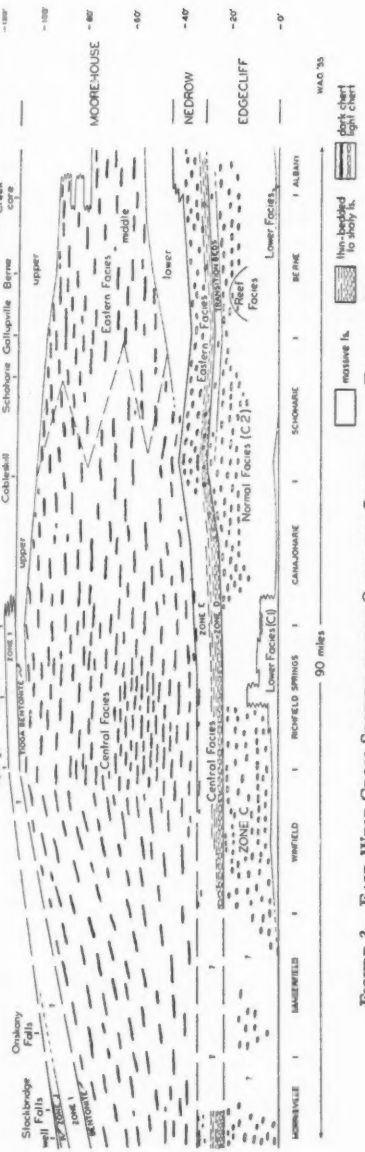

FIGURE 3.—EAST–WEST CROSS SECTION OF THE ONONDAGA LIMESTONE IN EASTERN AREA
Showing relationships of members, zones, and facies

New exposures on the New York State Thruway at the Saugerties interchange, 10 miles north of Kingston, indicate a minimum thickness of 162 feet.

In the outcrop belt between the Helderbergs and Kingston, structural complexities make measurements difficult. It is unlikely, however, that the Onondaga in this area is thinner than 110 feet, and southward it thickens to more than 160 feet near Kingston.

Between Kingston and Port Jervis exposures are too few and sections too incomplete for reliable measuring. The 200- and 250-foot thicknesses given by Shimer (1905, p. 192–193) and White (1882, p. 119) for the Port Jervis region include up to 200 feet of the underlying Schoharie formation (Goldring and Flower, 1942, p. 687–689). Goldring and Flower estimated 250–300 feet of Onandaga above the Schoharie, but no exposures are available for measurement. Willard (1939, p. 144, 155) reported a 200-foot thickness in adjacent New Jersey and Pennsylvania.

The general thickening seems to continue from the Helderbergs (110+ feet) south to Kingston (160+ feet) and to Port Jervis (est. 200 feet), although no accurate measurements can be made in the Port Jervis area.

BASAL CONTACT

The pre-Onondaga stratigraphy in most of the area studied has been discussed by Goldring and Flower (1942). From the Helderbergs to Port Jervis the Schoharie formation is closely related to the Onondaga. The contact is nowhere abrupt, and Goldring and Flower refer to transition beds ranging in thickness from a few inches at the north to several feet at the south.

The Schoharie has long been considered an eastern facies of the lower Onondaga. The Edgecliff (lowest) member of the Onondaga has been traced throughout this area. It thins from about 30 feet in the Helderbergs to a few feet at Port Jervis, while the lithology shifts from light gray, coarsely crystalline to medium dark gray and fine-grained. The upper part of the Schoharie at Port Jervis is equivalent to most of the Edgecliff farther north, but it is unlikely that the Schoharie is anywhere younger than the Edgecliff.

West of the Helderbergs the Schoharie thins

from 8 feet in the Berne quadrangle to 3 feet at Cobleskill. The same gradational zone, a few inches thick, is present wherever the contact is exposed. Some 7 miles west of Cobleskill in a small quarry 2.8 miles south of Sharon Springs the Schoharie is again present, 2.5 feet thick but separated from the Onondaga by a zone of phosphate nodules indicating slight disconformity.

West of Cobleskill, except for the one locality mentioned the Onondaga rests on the Carlisle Center formation. The contact is abrupt, but except at one place there is no indication of an erosional break. In the abondoned quarry just north of Springfield Four Corners, Richfield Springs quadrangle, the top of the Carlisle Center is marked by a zone of phosphate nodules and glauconite. The succeeding 2 feet of shaly, gritty limestone is lithologically similar to the Schoharie, but referred to the Edgecliff for reasons given below. This disconformity and the one south of Sharon Springs may represent localized areas of nondeposition at different times, or they could mark a single regional break correlative with the unconformity at the base of the Onondaga in the central area (Oliver, 1954, p. 625–626). The phosphate-nodule zone is not continuous, but the sharp break noted between the Carlisle Center and Onondaga may represent the same horizon.

West of the Richfield Springs quadrangle the Onondaga unconformably overlies various formations. This break has been extensively described elsewhere (Oliver, 1954, p. 625–626).

Edgecliff Member

Introduction

The Edgecliff member was named by Oliver (1954, p. 626) from exposures in Edgecliff Park, southwest of Syracuse, Onondaga County, New York. The park was undoubtedly named from a small cliff formed by the member which continues from the park to Split Rock about 2 miles to the east. The name is appropriate because of the member's resistance to erosion. It outcrops more persistently from the type area east to the Helderbergs than any other part of the formation, and small escarpments commonly indicate its presence.

In the central area the Edgecliff is a light gray, in places pink, coarse-grained limestone, occurring in beds from half a foot to 3 feet in thickness. Light-gray chert is common in the upper part, but in places, especially toward the east, is found throughout the unit. The Edgecliff is characterized by solitary rugose and tabulate corals, which are commonly so abundant as to form a coral biostrome. Crinoidal debris forms the matrix, and certain large (three-fourths inch) columnals are characteristic. Brachiopods are found at most exposures but are not common. The thickness of the unit ranges from 8 feet near Syracuse to 25 feet at Chittenango Falls, some 20 miles east.

Lower Edgecliff

In the central area two Edgecliff zones are recognized. Zone A (Springvale horizon) is a sandy bed representing reworked Oriskany sandstone. The unconformity to which this zone is related does not continue into the area under consideration, and neither does the zone. Zone C is the massive, gray, coralline limestone described above, and this zone can be recognized across the eastern area and as far south as the Coxsackie quadrangle.

The eastern Edgecliff can be subdivided. In the Winfield, Richfield Springs, and Canajoharie quadrangles the lower Edgecliff is markedly finer-grained and somewhat darker than the typical Edgecliff. To avoid confusion with central area designations the two divisions can be referred to as units C1 (lower) and C2 (upper, typical). Unit C1 is medium gray and rather fine-grained. It contains many of the corals that characterize the upper Edgecliff, but they are never abundant. Brachiopods and other forms are even less common than in unit C2.

The lower Edgecliff (C1) reaches a maximum thickness of 10 feet in the area around East Springfield (Richfield Springs quad.) but thins abruptly eastward and westward. On the east edge of the quadrangle at Cherry Valley the thickness is 6 to 7 feet; but south of Sharon Springs, 7 miles farther east, it has thinned to 1 foot; and is not more than a few inches thick east of the Canajoharie quadrangle. West of East Springfield unit C1 thins to 3–4 feet at the edge of the quadrangle and maintains a thickness of 3 feet across the Winfield quadrangle. The unit has not been definitely recognized

farther west, although the lowest Edgecliff at Oriskany Falls (Sangerfield quad.) and Chittenango Falls (Cazenovia quad.) is slightly finer-grained and darker than is typical in the central area.

Chert is sparse in the lower Edgecliff. One occurrence is in a ravine 2.75 miles north of Cherry Valley on the line separating the Richfield Springs and Canajoharie quadrangles where the Edgecliff outcrops at the top of a waterfall. Near the top of unit C1 there is a 6-inch light brownish-gray chert bed that is charged with rugose corals, both solitary and colonial. *Synaptophyllum simcoense* is the most common and persistent, but *Cystiphylloides* and other Edgecliff types are present. This chert can be traced a mile west along the Edgecliff escarpment and more than 2 miles to the southeast in the same position and with the same characteristics. Three miles west of Cherry Valley, in a small quarry 1 mile south of East Springfield, a concentration of corals in a partly chertified bed at the base of unit C2 may represent the same horizon.

In an abandoned quarry just north of Springfield Four Corners (Richfield Springs quad.) the base is defined as an unconformity represented by phosphate nodules. The complete Edgecliff section is as follows:

	Ft.	In.
Nedrow member		
Edgecliff member:		
8. Unit C2 (lithology described in text)	12	4
7. Unit C1 (lithology described in text)	9	4
6. Crumbly shale		9
5. Limestone bed (unit C1 lithology)	1	4
4. Shale		10
3. Black chert bed		4
2. Tan and gray shale and limestone		9
1. Phosphate nodules in glauconitic siltstone		3
Carlisle Center formation		

Beds 1, 2, and 3 contain a platyceratid-brachiopod fauna that is strikingly similar to that of the Nedrow member which overlies the Edgecliff. Only a few fossils have been found in the succeeding 3 beds: 4, no fossils; 5, *A. reticularis*, *Odontocephalus* sp., trilobite undet., horn coral, 2 ostracods; 6, *Atrypa reticularis*, one specimen. Bed 5 has the lithology of zone C1, and the fauna is what might be obtained from any bed of comparable thickness in that zone. Although the fauna could be Schoharie or Onondaga, the lithology indicates an Onondaga facies.

Beds 1–3, however, are unlike the overlying beds. No comparable lithology has been noted elsewhere except in a core recovered by the College of Ceramics from Shadow Brook, 2.9 miles south-southeast of the quarry. Here a bed of black chert occurs at the base of the Edgecliff. This indicates that there may be similar basal beds, but no exposures are available for study.

Beds 1–3 might be referred to the Schoharie because of their lithology and position below typical Edgecliff. Platyceratid gastropods predominate in the fauna. Some of the same species characterize the Nedrow member, and none of them have been reported from the Schoharie in eastern New York. The fauna indicates certain environmental conditions that were partly reproduced during Nedrow deposition, but which were unlike those of the Schoharie farther east. It seems best to place the Onondaga contact at the base of the phosphate nodule bed (1). This is the top of the Carlisle Center formation, which underlies the Edgecliff in surrounding areas.

Upper Edgecliff

Overlying the lower Edgecliff (C1) in the eastern area is the light- or light-medium gray, coarse-grained, coral zone that is most similar to the central-area Edgecliff. Light-gray chert is generally abundant, in the upper part of the zone but may occur throughout or be absent. In the Winfield quadrangle chert is present throughout the unit. To the east, in the western part of the Richfield Springs quadrangle, the lower 3 feet of the upper Edgecliff is noncherty, and midway across the quadrangle the whole unit lacks chert. In the Canajoharie quadrangle, next east, chert nodules are scattered through most exposures, and on the eastern edge of the quadrangle the upper half is cherty, which condition is typical also of exposures in the Schoharie, Berne, and Albany quadrangles. The distribution of chert is not paralleled by changes in the limestone, which has a persistent lithology throughout the eastern area.

The thickness of the upper Edgecliff (C2) is

variable, but the thickness of the member is uniform. Across the Winfield, Richfield Springs, and Canajoharie quadrangles the member is 20–23 feet thick, in general thickening eastward. In the same area the lower Edgecliff, absent in places, ranges up to 10 feet in thickness, and the upper Edgecliff from 10 to 23 feet in thickness. This indicates that unit C1 is laterally equivalent to the lower half of unit C2 farther east or west, and does not represent an earlier deposit (Fig. 3).

Farther east the Edgecliff is 30 feet thick at Cobleskill (Schoharie quad.) and maintains a 27- to 30-foot thickness east to the Countryman Hill section (Albany quad.).

The upper Edgecliff is characterized by numerous solitary rugose and tabulate corals, which are only occasionally as closely packed as they are in the central area. Crinoidal debris forms the matrix, and certain large columnals are characteristic. The columnals and corals are in general the same as those of the central area (Oliver, 1954, Table 1). The greatest difference noted is the common appearance of *Blothrophyllum decorticatum* and the scarcity of *Bethanyphyllum robustum*, rare and very common respectively in the central area. Identification and detailed study of the corals is in progress.

Bioherm Facies

One of the most interesting aspects of the eastern Onondaga is the presence of numerous bioherms in the Edgecliff member. These are lenticular or dome-shaped masses, generally circular in plan view, and range in diameter from 30 to 1200 feet and in thickness from 10 to 70 feet. The most striking of these forms Mount Tom in the northwest corner of the East Springfield 7½-minute (Richfield Springs, 15 min.) quadrangle. The Mount Tom reef is 700 feet long by 500 feet wide, and 70 feet thick. The lithologic characteristics are distinctive; bedding is absent, but contacts between colonies give a pseudobedding that dips irregularly in all directions; the reef rock is very light gray to medium gray, but is generally lighter-colored than the normal Edgecliff.

The bioherms are characterized by a variety of colonial rugose corals, only one of which is common elsewhere in the Onondaga. In addition many of the nonreef solitary rugose and tabulate corals are found on the reefs. The matrix is crinoidal, generally coarser-grained than elsewhere, and large stems are common. Forms other than corals are locally common and may be more abundant than in the normal Edgecliff (Table 1). The following four brachiopods, rare or unknown elsewhere in the Edgecliff, seem particularly characteristic of the reefs: *Camarotoechia tethys*, common; *C.* sp. and *Atrypa* sp. (sub-biconvex), frequent; and *Fimbrispirifer divaricatus*, common locally. Three species common elsewhere in the Onondaga and present in the Edgecliff have not been found in the reefs: *Levenea lenticularis*, *"Spirifer" duodenarius*, and *Pentagonia unisulcata*. Other brachiopods (Table 1) are found in both facies, but most of them are more common in younger members.

Platyceratid gastropods, including species of *Platyostoma*, *Platyceras*, and *Orthonychia*, are locally associated with the reef deposits. These are particularly characteristic of the Nedrow member overlying the Edgecliff and might indicate that reef growth persisted into Nedrow time. Most of these forms, however, have been found in upper, peripheral portions of the reefs and may represent Nedrow deposits plastered on the defunct reef.

The reef rock grades laterally into the normal Edgecliff. In several places a reef-flank zone several hundred feet wide is recognized. This zone is composed of both reef and off-reef forms. The reef corals are commonly overturned and may have fallen or slid from the reef. These flanking beds dip outward in all directions at angles up to 10°.

Wherever fully exposed the reefs rest on earlier bedded Edgecliff but may be overlain by Edgecliff or younger beds depending on the size of the reef. Some of the larger ones are overlain by the Moorehouse member, indicating that Nedrow deposits were not sufficient to bury the structure. The overlying beds tend to dip away from the reef and are probably thinner than normal across the reef. Exposures are not extensive enough to demonstrate this except where the Nedrow is absent over the larger reefs.

Twenty-one bioherms have been recognized

in eastern New York. Their greatest concentration is in the Richfield Springs quadrangle where 10 are known, but others occur in each of the quadrangles east to Albany and in the northern half of the Coxsackie quadrangle. These reefs have been described individually and in detail by Oliver (1956). There is little variation, except in size, from one reef to another. The corals and large crinoid columnals are invariably present, and differences in faunas from one reef to another seem to be due to accidents of discovery. Within even the largest reefs no distribution pattern of species has been found.

Southeastern Facies

The Edgecliff (C2) lithology is recognized as far east as the Albany quadrangle. To the south, in the northern half of the Coxsackie quadrangle, there are three large reefs, two of which show the flanking facies. No good exposures of normal Edgecliff are known south of the reefs.

In the southern half of the quadrangle and farther south the Edgecliff is recognizable, but it is so altered that it is referred to as the southeastern facies. This facies is well exposed at Leeds, in the southern part of the Coxsackie quadrangle. Here 36 feet seems definitely referable to the Edgecliff. The section is as follows (Fig. 4):

	Ft.	In.
Nedrow member		
Edgecliff member:		
5. Medium-gray, medium-grained limestone with abundant light-gray chert; corals present, becoming common in the upper 4 feet; platyceratids rare in upper 4 feet; typical large crinoid columnals common; *Hindia* sp. present.	15	6
4. Light-gray, medium-grained limestone with abundant light-gray chert; corals rare; typical large columnal common.	8	
3. Medium-gray, medium fine-grained limestone, with abundant chert. Corals and typical large columnal are present.	9	
2. Medium-gray, medium fine-grained limestone; no chert.	3	6
1. Medium-gray, medium fine-grained, gritty limestone; forms transition to	1	4
Schoharie formation (see Goldring and Flower, 1942, p. 684–685, for description).		

The lithology is similar to that of the typical Edgecliff. The lower 12½ feet of darker and finer-grained limestone above the transition zone is analagous to unit C1 of the Richfield Springs quadrangle, and the upper 23½ feet may be compared to unit C2. Corals are comparatively scarce, however; a few of the same types are found in the lithologically similar, overlying Nedrow member. The latter however contains the typical platyceratid fauna and can be recognized on this basis. The large crinoid columnal is found only below the platyceratid beds, especially in the lower Edgecliff, and is believed to be characteristic of the Edgecliff across the State.

Farther south the Edgecliff is exposed in several places but only a few are complete sections or show a lithologic change. The entire member is exposed in a new road cut on the New York State Thruway just south of the Saugerties interchange (Route 212). Collecting is difficult in the fresh, vertical exposures, and the dips are steep (30°) and variable. The sequence is the same as at Leeds: 3 feet 4 inches of medium-gray, medium fine-grained limestone is overlain by lighter and coarser-grained limestone with abundant light-gray chert. The lower 14 feet of the latter has a few corals, and the large columnal is fairly common. The succeeding 25–30 feet is similar in lithology, but no diagnostic fossils were collected from the fresh cuts. The upper Nedrow is recognizable, however, and the combined Edgecliff-Nedrow thickness is about 61 feet as compared to 78 feet at Leeds. It is unlikely that either of the members has thickened toward the south, so the Edgecliff thickness at Saugerties is estimated at 27 feet, although only 17 feet are positively identified.

Several small, partial sections in and around Kingston, 10 miles south of Saugerties, show no lithologic change. Ten miles farther south-southwest on Route 209 at the Marbletown-Rochester town line (Rosendale quad.) a minimum of 10 feet was measured above the Schoharie transition. The lower, finer-grained unit is 5 feet thick.

In a small abandoned quarry in Wawarsing (Slide Mountain quad.) 12 miles southwest of the last locality the complete Edgecliff is exposed. The section is as follows (*see* Fig. 4):

	Ft.
Moorehouse member	
Edgecliff member:	
4. Medium-gray, medium fine-grained limestone; corals frequent, none diagnostic of the Edgecliff; large columnal common (diagnostic); brachiopods and Bryozoa rare.	6
3. Limestone similar to above with small scattered chert nodules; corals common (none diagnostic); large columnals common (diagnostic).	3
2. Limestone similar to above, no chert; poorly exposed but characteristic columnals are present.	3–4
1. Schoharie transition; brown weathering, siliceous. (Base of section in quarry.)	2–3

This interpretation differs from that of Goldring and Flower (1942, p. 687). They referred the lower 35 feet of limestone in the quarry to the Schoharie formation and remarked that the lithology throughout the quarry was "finer-grained than typical for the Onondaga." The Schoharie-Onondaga separation cannot be made on lithologic characteristics at this locality. The presence of the characteristic large columnals, which are indicative of basal Onondaga elsewhere, and the fact that overlying beds have lithologic characteristics typical of the Moorehouse member support the present correlation.

No complete section is known farther south in New York. At Trilobite Mountain, just east of Port Jervis, most of the section referred to the Onondaga by Shimer (1905, p. 192–193) is actually Schoharie (Goldring and Flower, 1942, p. 687–698). There are exposures in the area between the roads on the southeast side of the Neversink Valley (adjacent to the Golf Club) on the Port Jervis quadrangle. Goldring and Flower (1942, p. 689) refer the upper 17 feet to the Schoharie but state that they might be considered transition beds. The upper 7 feet is medium dark-gray, fine-grained limestone with considerable black chert and contains the following fossils:

Large Edgecliff columnal	common
Heterophrentis cf. *prolifica*	rare
Small zaphrentids	frequent
Atrypa reticularis	frequent
Leptaena rhomboidalis	rare
Spirifer raricostus?	rare
Platyostoma sp.	frequent
Ceratopora sp.	
Favosites sp.	
Rhipidomella sp.	
"*Spirifer*" sp.	
Phacops sp.	

None of these are diagnostic, but the large columnals again seem to indicate that these beds are Edgecliff. The last five forms were not found by the author but are listed by Goldring and Flower (1942, p. 688–689).

The top 7 feet of the Trilobite Mountain section represents the culmination of the southerly changes that began in the Coxsackie quadrangle. South from Leeds the Edgecliff thins, the coral fauna disappears, the rock becomes finer-grained and darker, and the light-gray chert is replaced by dark chert. In most respects the Port Jervis Edgecliff is similar to the Moorehouse and upper Schoharie units. The persistence of the large columnal is remarkable and suggests that the Schoharie formation of southeastern New York is not younger than the Edgecliff member in the Helderbergs.

Fauna

The species identified by the author from the Edgecliff member in eastern and southeastern New York are listed in Table 1. The corals are not listed because critical study is underway and lists based on current knowledge would be of dubious value. The most obvious faunal characters of each facies have already been indicated, but the following summary may be of help.

The rugose corals are the most important single group. Large solitary forms are abundant in the normal facies, and in places the unit is almost a biostrome. The corals form a characteristic assemblage that does not occur elsewhere in the Onondaga. In the southeastern facies the robust Edgecliff types are gradually replaced to the south by small zaphrentids, similar to those found in the Moorehouse member. Colonial rugose corals characterize the bioherm facies but with one exception, are rare elsewhere in the Onondaga. The rugose corals are environmentally controlled, and many are found wherever the proper facies is developed in the Onondaga. Post-Edgecliff bioherms are not known. Many of the solitary rugose corals are present in similar facies of the Moorehouse member, but never in comparable numbers.

Tabulate corals are common in the normal (C2) and bioherm facies. The same species are found in the lower Edgecliff (C1) and the southeastern facies, but are nowhere common. These also are found in younger members where lithologically similar to the upper Edgecliff.

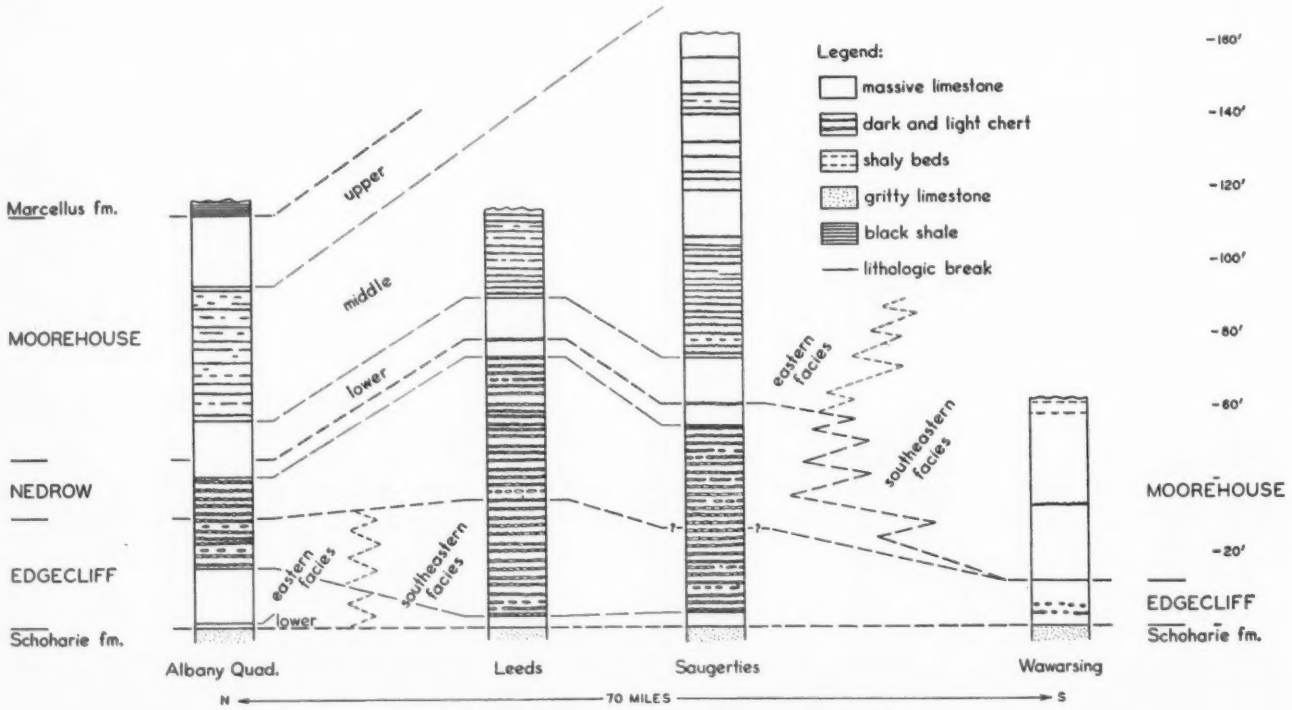

FIGURE 4.—ONONDAGA SECTIONS IN THE SOUTHEASTERN AREA

Showing the relationships between lithologic and paleontologic units. The left-hand column is generalized for the Albany quadrangle.

TABLE 1.—EDGECLIFF FAUNA

Facies	Normal facies	Flanking facies	Reef facies
Corals			
Solitary rugose	vc	vc	c
Colonial rugose	..	c	vc
Tabulate	c	c	c
Bryozoans			
Fenestellate	x	x	c
Branching	..	..	vr
Massive	vr	r	x
Brachiopods			
Levenea lenticularis	r	vr	..
Rhipidomella sp.	vr	..	vr
Isorthis propinqua	vr	..	..
Pentamerella arata	vr	vr	vr
Megastrophia hemisphaerica (= *concava*?)	vr	vr	..
Cymostrophia patersoni	..	..	vr
Stropheodonta demissa	..	..	vr
S. inequiradiata	vr	vr	?
Protoleptostrophia perplana	vr	vr	vr
Leptaena rhomboidalis	vr	..	r
Schurchetella pandora	r	..	x
Choneles hemisphericus?	vr	..	..
C. mucronatus	vr	..	r
Camarotoechia tethys	..	..	c
C. sp.	?	..	r
Atrypa reticularis	x	vc	c
A. sp. (biconvex form)	..	..	r
Coelospira camilla	vr	..	..
Elytha fimbriata	vr	vr	r
Fimbrispirifer divaricatus	..	..	c[1]
"*Spirifer*" *duodenarius*	r	vr	vr
"*Sp.*" *grieri*	vr	..	..
"*Sp.*" cf. *manni*	..	vr	c
"*Sp.*" *raricostus*	x	x	r
Ambocoelia umbonata	vr	..	..
Meristella doris	?	?	vr
M. nasuta	x	vr	vr
M. scitula	..	..	vr
M. sp.	vr	..	vr
Pentagonia unisulcata	r	vr	..
Athyris spiriferoides?	..	vr	..
Amphigenia elongata	r	vr	vr
Terebratula lens	..	..	vr
Gastropods			
"*Pleurotomaria*" *plena*	vr	..	..
"*P.*" sp.	..	..	vr
Platyostoma lineatum	vr	vr	vr
P. turbinatum	vr	x	r
P. turbinatum var. *cochleatum*	..	..	vr
Platyceras argo	..	..	vr

TABLE 1.—*Continued*

Facies	Normal facies	Flanking facies	Reef facies
Gastropods—*Continued*			
P. carinatum	..	..	vr
P. dumosum	vr	..	..
P. erectum	vr	vr	vr
P. rictum	..	..	vr
P. cf. *undatum*	vr	..	..
P. sp. unidentified	vr	r	vr
Orthonychia sp.	vr	..	r
Cephalopods			
Gyrocones	vr	..	..
Pelecypods			
Conocardium cuneus	vr	..	..
C. trigonale	..	..	vr
Aviculopecten? sp.	..	..	vr
Trilobites			
Odontocephalus sp.	r	r	vr
Euarges contusus	..	..	vr
Phacops cristata	vr	..	vr
P. pipa	..	..	vr
P. sp.	vr	r	..
Dechenella halli	vr	..	vr
D. cf. *macrocephalus*	..	..	vr
D. microgemma	?	..	vr
"*Proetus*" sp.	vr	r	vr
Cyphaspis sp.	vr	..	vr

vvc. Abundant (crowded in rock)

vc. Very common (common throughout unit)

c. Common (present or common at most exposures of unit)

x. Frequent (few specimens found at most exposures of unit)

r. Rare (uncommon, found at approximately half the exposures)

vr. Very rare (one or two specimens at few localities)

[1] Locally

Pelmatozoan debris, presumably crinoidal, forms much of the matrix in the normal and biohermal facies. The large crinoid columnal, which is so characteristic of the Edgecliff in all its facies, has not been found attached to a calyx and no calyx described from the Edgecliff would be large enough to match this stem. Hall illustrated this columnal (1843, p. 157, Fig. 3), which he described (p. 158) as "an abundant and characteristic fossil of this rock." This form is found in all facies of the Edgecliff

and is not known elsewhere. Where the Edgecliff is not lithologically distinct the columnal is the only identifying character.

Brachiopods are common in the Edgecliff, but few are restricted to one facies. A few forms have been mentioned as apparently characteristic of the normal or bioherm facies, but none are common enough to identify either facies. In the lower Edgecliff (C1) and the southeastern facies, brachiopods are more significant, but only because of the lack of corals.

Platyceratid gastropods, of uncertain significance in the reef facies, are uncommon elsewhere in the Edgecliff and rare in the southeastern facies. Only a few pelecypods and cephalopods have been found. Several trilobites have been identified, but none is known to be characteristic of a particular facies. Bryozoans are common, notably fenestellate types in the normal (C2) and bioherm facies but have not been studied in detail.

Nedrow Member

Introduction

The Nedrow member was named by Oliver (1954, p. 627) from exposures in the Indian Reservation quarry, 1 mile south of Nedrow, Onondaga County, New York. Throughout the central area the unit consists of a lower shaly zone (D), which grades upward to more massive fine-grained limestone in beds 2 to 6 inches thick (zone E). Zone D is characterized by an abundance of platyceratid gastropods that are present in diminishing numbers upward in zone E. Bachiopods are present in even greater numbers and variety but are not diagnostic. Zone E is less fossiliferous than zone D, but essentially the same fauna is present. The thickness of the member ranges from 10 to 15 feet.

The Nedrow member can be traced east to the Helderbergs and south to Kingston. As far east as the Canajoharie quadrangle the lithology is much the same as described above and can be referred to the central facies. Farther east the lithology changes gradually, although the platyceratid fauna continues. This is called the eastern facies.

Central Facies

Because of the contrast between the massive Edgecliff and shaly Nedrow, the former commonly crops out while the latter is stripped back to form a gentle slope above. In consequence exposures are few and poor in certain areas. Only two small partial sections are known in the Morrisville, Sangerfield, and Winfield quadrangles (Fig. 1). Good exposures in the Richfield Springs quadrangle are separated by 50 miles from the next complete sections to the west (Chittenango and Cazenovia quads). In the intervening area the relief is generally low, the glacial cover is thick, and bedrock exposures are few and far between. Only the resistant Edgecliff can be satisfactorily traced across the area; the higher members outcrop in only a few places. However, the Nedrow is so uniformly developed on either side of this gap that it is assumed that the central facies is continuous through this area.

In the Richfield Springs quadrangle the best exposure is in the creek bed just south of the Oliver Cemetery, 0.8 mile south of East Springfield (shown on the East Springfield 7½-minute quad.). The section is as follows:

	Ft.	*In.*
Moorehouse member, scattered exposures upstream		
7. Covered	6	5
Nedrow member:		
6. Medium-gray, fine-grained limestone with several black chert-nodule horizons; sparse Nedrow fauna with a few Moorehouse types.	5	
5. Tan-weathering, shaly to thin-bedded limestone, with platyceratid fauna.	6	
4. Covered, probably shaly Nedrow.	4	
Edgecliff member:		
3. Covered, probably Edgecliff.	1	
2. Zone C2.	8	4
1. Zone C1.	9	
Carlisle Center formation		

A small quarry just south of the creek indicates that at least 1 foot of the covered interval above the Edgecliff should be referred to the Edgecliff. The remaining 4 feet are probably the less resistant lower shaly beds of zone D. A cored section in Shadow Brook 1.6 miles southwest of this locality showed 10 feet 8 inches of lower, noncherty Nedrow, which fits in well with the above interpretation. The upper 5 feet in the Oliver Cemetery section is more massive and represents a gradation to Moorehouse condi-

tions. A large gyroconic nautiloid is indicative of the latter.

This is the typical central facies sequence, and the two divisions are referred to as zones D and E. A complete section of the Nedrow is exposed in the Springfield Four Corners quarry, but collecting is difficult in the vertical wall. The 15-foot thickness seems uniform throughout the quadrangle.

Three exposures are known in the Canajoharie quadrangle, but only one is suitable for detailed study. On the north side of the village of Cherry Valley, a small triangle is formed by two roads and the Delaware and Hudson Railroad tracks (Sprout Brook, 7½-minute quad.). Within this triangle is a small quarry in the upper Edgecliff (C2), and just south of this, across the tracks, is a small cut in the Nedrow. The thickness and sequence is the same as in the Richfield Springs area.

The Nedrow is again exposed in a creek between the roads, 0.2 mile north of the Dutch Reformed Church in the southwest corner of the Sharon Springs 7½-minute quadrangle. Here exposures are poor, but are still of the central facies. At Cobleskill (Schoharie quad.), 10 miles southeast of the Dutch Church exposures, the Nedrow first shows important changes from the type area and is referred to the eastern facies.

So far as can be determined, the central facies of the Nedrow maintains a thickness of 12 to 15 feet. The two-fold division is characteristic; the lower (D) representing markedly different depositional environment from either the Edgecliff or Moorehouse members, and the upper (E) marking the transition to Moorehouse conditions. The platyceratid fauna is characteristic of zone D, but persists in zone E. The lower contact is a marked lithologic break, but the upper is gradational and is based mainly on the fauna.

Eastern and Southeastern Facies

Beginning in the Schoharie quadrangle and reaching its most distinct development in the Helderberg area, the Nedrow lithology becomes more and more like that of the underlying Edgecliff, and in the Albany to Rosendale quadrangles (Fig. 2) the member can be differentiated only on the basis of its fauna. The change is first noted at Cobleskill. In two abandoned quarries, one on the northeast side of the village and the other 1.3 miles northeast of the main intersection in town, the member is well exposed. The section at the second of the two is as follows:

	Ft.	In.
Top of quarry		
Nedrow member:		
8. Medium-gray, fine-grained limestone with considerable medium-gray chert in nodules and discontinuous beds. Thinner-bedded in lower part, transitional to	9	
7. Tan-weathering, thin-bedded limestone with platyceratid fauna	4	
Edgecliff member:		
6. Light medium-gray, medium coarse-grained limestone with several light-gray chert beds; brachiopod fauna may indicate transitional nature of these beds	3	
5. Limestone similar to 6 with chert (zone C2)	11	7
4. Limestone similar to 6 without chert (zone C2)	13	
3. Medium-gray, fine-grained limestone (zone C1?), transitional downward to	2	6
Schoharie formation:		
2. Limestone similar to 3, gritty	1	6
1. Soft shale		9
Carlisle Center formation		

The lower part of this section has been discussed by Goldring and Flower (1942, p. 675–676), and is included here to show some small adjustments of their section. Bed 6 probably correlates with a similar gradational zone in the Berne and Albany quadrangles. Bed 7 is less shaly than zone D of the central facies, but is certainly analogous since the greatest concentration of platyceratids is here. The platyceratids are present through at least the lower 7 feet of 8. Higher beds in the other quarry nearer Cobleskill seem referable to the Moorehouse, so the Nedrow thickness is 11–13 feet in this area.

The Nedrow is exposed at a few other places in the Schoharie quadrangle, but none of these is complete or provides any new information. The member is well exposed in a ravine 0.9 mile south-southwest of Gallupville, Berne quadrangle (Gallupville, 7½-minute quad.). The section there is as follows:

	Ft.	In.
Moorehouse member, scattered exposures higher		
8. Covered	4	10
7. Medium light-gray, medium coarse-grained limestone	6	
Nedrow member:		
6. Limestone similar to 7 with light-gray chert beds; sparse platyceratid fauna	7	
5. Limestone similar to 7, thin-bedded with shaly partings, scattered light-gray chert nodules; platyceratid fauna	3	
Edgecliff member:		
4. Limestone similar to 7, more massive; light-gray chert beds; sparsely fossiliferous	3	
3. Medium dark-gray, fine-grained limestone, one chert bed; few corals and other fossil fragments	1	6
2. Light-colored, coarse-grained limestone with light-colored chert	1	8
1. Light-colored, coarse-grained limestone, no chert, corals common	4	
Covered		

This is similar to the Cobleskill section. Zones D and E are more or less recognizable, and bed 4 seems to correspond to the Edgecliff-Nedrow transition at Cobleskill (bed 6). At Gallupville, however, the transition is better developed. Beds 3 and 4 do not have the characteristic lithology of either member, but bed 3 has a few corals and may be called Edgecliff.

Farther east, in the Helderbergs (Albany quad.) the upper Nedrow is represented by the same coarse-grained, light-colored, cherty limestone that is characteristic of the Edgecliff, but the lower Nedrow continues to be less resistant to weathering because of its thin bedding. The upper beds are best exposed in a road cut on Highway 34 on the northeast side of Copeland Hill. The section there is as follows:

	Ft.	In.
Moorehouse member:		
5. Light medium-gray, coarse-grained limestone	11	6
Nedrow member:		
4. Limestone similar to 5; Nedrow platyceratids and *Platyceras dumosum* (not diagnostic)	7	
3. Limestone similar to 5 with light-colored chert; platyceratid fauna	6	
Covered		

The lower beds occur in the Countryman Hill section in a road cut 1.2 miles southwest of New Salem:

	Ft.	In.
Covered		
4. Light-colored, coarse-grained limestone	12	
3. Limestone similar to 4 with light-colored chert, lower 2 to 4 feet thinner-bedded with platyceratid fauna	8	8
2. Light-colored, coarse-grained limestone with light-colored chert	2	10
1. Medium-gray, medium- to fine-grained limestone	1	8
Covered		

The exposures are vertical, and satisfactory collections were obtained only from the lower part of bed 3, which is essentially zone D. Below this are the same two upper Edgecliff beds noted at Gallupville. Above 3, 7 feet of 4 is Nedrow by analogy with the nearby Copeland Hill section. The total thickness of the Nedrow in this area must be about 15 feet. Correlation of the eastern sections is as follows:

Cobleskill		Gallupville			Countryman Hill Copeland Hill			General
Bed	Feet	Bed	Feet	Inches	Bed	Feet	Inches	
8	7	6	7	..	3,4	11	8	zone E
7	4	5	3	..	3	4	..	zone D
6	3	4	3	..	2	2	10	transition
...	....	3	1	6	1	1	8	dark layer

The thin-bedded platyceratid limestone corresponds to zone D of the central facies; the succeeding more massive beds with fewer platyceratids are zone E. Below zone D the transition beds must equate with upper Edgecliff beds west of Cobleskill. The dark layer is an excellent point of similarity between the eastern two sections but was not noticed at Cobleskill.

Between Cherry Valley and the Helderbergs 40 miles away, the lower Nedrow becomes more massive, the Nedrow limestone grades from medium gray, fine-grained to light gray, coarse-grained, and the chert grades from black through medium gray at Cobleskill to light gray. There is slight thickening toward the east.

TABLE 2.—NEDROW FAUNA*

Facies	Central			Eastern				S.E.	
Quadrangle	Win-field	Rich-field Spr.	Canajo-harie	Scho-harie	Berne	Albany	Cox-sackie	Catskill (incl. Leeds)	Rosen-dale
Sponge									
Hindia sp.	..	..	..	x	..	..	..	..	vc
Corals									
Small zaphrentids	..	x	x	x	x	x	x	x	x
Heliophyllum halli	..	..	r	r	r	..	..	..	r
Amplexiphyllum cf. *hamiltoniae*	..	..	..	r	..	?	..	..	..
Bryozoans	x	x	x	x	x	x	x	x	x
Fenestellate bryozoans	..	vr	..	x	x	x	r	..	..
Fistulipora sp.	..	..	vr	..	..	..	..	..	..
Massive bryozoans	..	..	..	..	r	r	r	..	..
Brachiopods									
Pentamerella arata	r	vr	x	..	x	..	..	r	..
Atrypa reticularis	r	c	c	x	..	x	r	c	x
"Spirifer" raricostus	r	vr	x	..	x	x	x	..	x
Nucleospira concinna	..	vr	..	..	..	..	..	..	..
Camarotoechia sp.	..	vr[u]	..	..	..	?	..	..	..
Megastrophia hemisphaerica (= *concava*?)	..	r[u]	..	vr	x	..	..	..	..
Levenea lenticularis	?	x	x	r	..	x[u]	..	..	..
Stropheodonta inequiradiata	..	r	x	x	r	vr	..	..	..
Chonetes mucronatus	..	x[u]	..	..	..	vr[u]	..	..	..
Atrypa spinosa	..	vr	?	..	?[u]	c[u]	..	..	..
Pentagonia unisulcata	..	r	x	r	x	c	r	..	..
Strophonella ampla	..	vr	vr	..	..	?	..	r	..
Leptaena rhomboidalis	..	vr	x	r	..	..	r	..	c
Coelospira camilla	?	..	vr	r	..	r	..	..	..
Discina? sp.	..	..	..	vr	..	..	..	..	..
Lingula cf. *desiderata*	..	..	..	vr	..	..	..	..	..
Protoleptostrophia perplana	..	..	..	vr	..	?[u]	..	..	..
"Spirifer" subumbonus	..	..	..	vr	..	..	..	..	..
Cymostrophia patersoni	..	..	..	vr	..	..	r	..	..
"Spirifer" duodenarius	..	..	..	vr	..	..	..	r	..
Meristella doris?	..	..	..	..	r	..	..	..	..
Schuchertella pandora	..	..	..	?	..	vr[u]	..	..	..
Elytha fimbriata	..	..	..	..	..	vr	..	..	..
"Spirifer" disparalis	..	..	..	..	..	vr	..	..	..
Meristella nasuta	..	..	..	..	..	vr	..	..	..
M. scitula	..	..	..	..	..	vr	..	..	..
Stropheodonta junia?	..	..	..	..	..	..	r	..	..
"Spirifer" manni	..	..	..	..	..	..	r	..	..
Centronella glansfagea?	..	..	..	..	..	..	r	..	..
"Spirifer" varicosus?	..	..	..	..	..	..	..	..	r
Gastropods and "pteropods"									
Platyostoma lineatum	x	..	?	vr	r	..	..	x	r
P. turbinatum	r	x	r	x	..	c	vc	x	c
Platyceras carinatum	r	..	r	c	..	..	x	..	x
Orthonychia dentalium	..	vr[u]	..	..	..	..	..	..	..
Platyceras nodosum?	..	..	r	..	..	..	..	..	..
P. fornicatum	..	..	r	x	..	..	..	..	..
Platyostoma sp. unidentified	..	..	vr	..	..	..	r	..	..
Platyceras sp. unidentified (not *P. dumosum*)	..	..	x	vc	vc	vc	c	x	c

TABLE 2.—*Continued*

Facies	Central			Eastern				S.E.	
Quadrangle	Winfield	Richfield Spr.	Canajoharie	Schoharie	Berne	Albany	Coxsackie	Catskill (incl. Leeds)	Rosendale
Gastropods and "pteropods" (cont.)									
"Pleurotomaria" sp.	..	..	..	vr	..	..	..	..	..
Platyceras argo	..	..	..	vr	..	..	..	..	..
P. cf. *echinatum*	..	..	..	vr	..	..	..	..	..
Orthonychia conicum	..	..	..	x	..	..	..	..	..
Styliolina cf. *fissurella*	?	..	..	r	..	..	..	..	..
Platyceras erectum	..	..	..	..	r	..	..	..	..
P. dumosum	..	..	?	..	?[u]	c	r	..	r
P. cf. *crassum*	..	..	..	..	..	..	x	..	..
Cephalopods									
Spyroceras cf. *multicinctum*	..	vr	..	..	..	..	..	..	..
Tornoceras cf. *buttsi*	..	r	..	..	..	..	..	..	..
Gyroconic nautiloids	..	vr[u]	r	..	..	..	..	..	..
Pelecypod									
Aviculopecten ignotus?	..	r[u]	..	..	..	..	..	..	..
Trilobites									
Phacops sp.	r	..	x	r	r	r	x	..	..
Odontocephalus selenurus	..	vr	..	..	..	..	..	..	..
O. sp.	..	vr	vr	..	..	vr	..	..	..
"Cyphaspis" cf. *craspedota*	..	..	..	..	..	vr	..	..	..
Dechenella halli?	..	..	..	..	..	..	r	..	..
D. microgemma	..	..	..	..	..	..	r	..	..
Phacops pipa	..	..	..	..	..	..	..	..	r
Unidentified trilobites	..	x[u]	..	r	x	x	..	r	..
Ostracods	..	..	x	x	x	r	..	..	..
Crinoid									
Dolatocrinus lobatus	..	..	..	vr	..	..	..	..	..

* *See* Table 1 for symbols

[u] Upper Nedrow only

Throughout, the platyceratids identify the member. In the central facies they are concentrated in the shaly 2–4 feet of the member; in the Helderbergs where no shaly zone is present they are common in the lower 9 feet.

These eastward changes culminate farther south. At Leeds (25 miles south) the member consists of light-colored, coarse-grained, cherty limestone which cannot be separated from the Edgecliff or the Moorehouse on lithologic characteristics. Some 43 feet of platyceratid beds are referred to the Nedrow. The thickness at Saugerties (13 miles farther south) is estimated to be 34 feet. Still farther south (10 miles) at Kingston the Nedrow has the same lithology and fauna as at Leeds; the thickness is unknown (Fig. 4).

No exposures of the Nedrow have been found farther south. At Wawarsing, 22 miles south-southwest of Kingston, the Moorehouse rests directly on the Edgecliff, and no Nedrow is present (*see* section under Edgecliff). In this distance both the Edgecliff and Moorehouse become darker, and it is probable that the platyceratids are absent because they could not adapt to the environment and that the Nedrow interval is represented by basal Moorehouse. The Edgecliff-Moorehouse contact is gradational.

Reef Flank Facies

The common occurrence of platyceratids in peripheral parts of some of the larger Edgecliff bioherms may indicate that the bioherm growth persisted into Nedrow time, but more likely that they still existed as positive features and were being buried. Nowhere have Nedrow beds been found extending across the top of the reefs. In many places the member was not thick enough, and burial was completed in Moorehouse time.

The relationships are best shown at two of the reefs. The first is located in the Richfield Springs quadrangle on the boundary between the Richfield Springs and East Springfield 7½-minute quadrangles, 1.7 miles north of Highway 20. The platyceratids occur in a light medium gray, coarse-grained limestone on the northwest edge of the reef. This is unlike the lithology of the Nedrow central facies and may indicate that the reef was eroded to supply much of the Nedrow sediment near the reef.

The second reef is in the Coxsackie quadrangle on both sides of the road, 0.3 mile west of a point 42° 25′ N. Lat. and 73° 50′ W. Long. In a small cliff 50–100 feet west of the reef Nedrow and Moorehouse beds outcrop. The exposure is typical eastern facies Nedrow. If projected toward the reef the Nedrow beds would terminate against it, while the upper part, at least, of the Moorehouse would lie above the reef.

The Nedrow-reef relationship is exposed at only a few other places. For the most part the known reefs are small hills from which the overlying beds have been stripped. It is evident that the platyceratids are not normal reef elements, and it seems likely that they were deposited after reef building ceased.

Fauna

The Nedrow fauna identified by the author is listed in Table 2. Each column represents two to four localities. The platyceratids are most significant, but more by their frequency and variety than by particular species. Only *Platyceras dumosum* is common in the Moorehouse. It is a facies fossil found in all members in eastern New York, usually in light-colored, coarse-grained beds. Several platyceratids are found in the Edgecliff, but they are not widespread.

In the central area the corals *Amplexiphyllum* cf. *hamiltoniae* and a low turbinate form of *Heliophyllum halli* are characteristic of the shaly beds of the Nedrow member. In the eastern Nedrow these species are less common, but *H. halli* has been found throughout the eastward extent of the member, and *A.* cf. *hamiltoniae* has been found as far east as the Schoharie quadrangle. Both species occur in the Edgecliff and rarely in the Moorehouse and Seneca, but are most common in the lower Nedrow (zone D).

Other corals and bryozoans are present in nearly all exposures but have not been studied, and their significance is not known. Brachiopods are more varied than the gastropods, but none is peculiar to the Nedrow member. Trilobites make important additions to the list, but none is characteristic of the member. Only the platyceratids are known to be more or less restricted to the Nedrow, and their persistence in all facies is remarkable.

Moorehouse Member

Introduction and Summary

The Moorehouse member was named by Oliver (1954, p. 628) from exposures in the Onondaga County Prison quarry at the southwest extremity of Moorehouse Flats, Jamesville, New York. In the type area the Moorehouse has a thickness of 20–25 feet. To the east and southeast the Moorehouse thickens out of proportion to the other members as shown in the following table:

Locality	Thickness in feet	
	Moorehouse	Onondaga fm.
Type area	20–25	65–70
Morrisville quad.	40–45	85–90
Cherry Valley, Canajoharie quad.	75	118
Onesquethaw Creek, Albany quad.	67+	111+
Saugerties	100+	162+
Port Jervis	est. 190	est. 200

In the central area the Moorehouse is a medium-gray, fine-grained limestone with black chert throughout but especially abundant in the

upper half. The unit is characterized by a variety of brachiopods and contains a greater number of species and individuals than any other member. A peculiar gastropod fauna is found in the chert beds of the upper half of the member, and the greatest number and variety of other fossils are in the limestone beds of the upper half. On the basis of the chert and fossil distribution the Moorehouse was divided into a lower zone (F) with sparse chert and fewer fossils and an upper zone (G) with abundant chert and a variety of brachiopods and other fossils (Oliver, 1954, p. 628). These zones are approximately equal in thickness. Large coiled cephalopods, *Halloceras undulatum* and others, are characteristic of the member.

With the thickening in the eastern area the significance of zones F and G is lost, and no general zonation of the eastern Moorehouse has been established. Far more interesting than any vertical changes are the horizontal changes. The Moorehouse in the Helderbergs (Berne-Albany quads.) is quite different from the type Moorehouse. This lateral change takes place in the Schoharie quadrangle.

In the Berne and Albany quadrangles the Moorehouse member is divisible into 3 parts on the basis of lithology: an upper noncherty division, a middle cherty division, and a lower noncherty division. To the west in the Schoharie quadrangle the lower noncherty division grades westward into cherty limestone identical to that of the middle division. The upper noncherty division thins to the west as the chert appears higher and higher in the formation. In the Richfield Springs and Canajoharie quadrangles the upper 5–8 feet of the Moorehouse is noncherty, but black chert is found throughout the rest of the member and in the uppermost 2 or 3 feet of the Nedrow (Fig. 3). In the central area the chert is found throughout the Moorehouse and in the overlying Seneca member.

Central Facies

West of the Schoharie quadrangle the limestone is generally medium gray and fine-grained and occurs in beds from 1 to 10 inches in thickness. The uppermost beds are medium light gray, somewhat coarser-grained and noncherty. Local variations in lithology are recognized. The chert may occur in 2–4 inch beds spaced 2 feet apart or may make up 30–40 per cent of the rock. Such differences do not persist horizontally.

The member is characterized by an abundance of a variety of brachiopods, gastropods, cephalopods, and trilobites (Table 3). These are common in many outcrops, sparse in others. No consistent fossil zonation has been found. Slight differences appear in the upper noncherty division. The fauna of this unit is listed separately because of more important differences farther east.

The member is 75 feet thick at Cherry Valley (core), and the thickness is rather uniform across the Richfield Springs and Canajoharie quadrangles. The upper division is 5 feet at Cherry Valley and thickens to 8–10 feet at the eastern margin of the Canajoharie quadrangle.

Eastern Facies

In the Berne quadrangle the Moorehouse is quite different from the central facies. It is best exposed in the creek in Berne Village where the section is as follows (thicknesses from R. Digman, personal communication):

	Ft.
5. Covered	
4. Light medium-gray, medium coarse-grained limestone	17
3. Medium dark-gray, fine-grained limestone with black chert	38
2. Light medium-gray, medium coarse-grained limestone	13
1. Limestone similar to 2, with light-gray chert (Nedrow?)	2

By analogy with near-by sections bed 1 should be uppermost Nedrow although the typical fossils were not found. The succeeding 3 divisions are sufficiently distinct lithologically to be considered subdivisions of the Moorehouse.

The lateral change from central to eastern facies takes place in the Schoharie quadrangle where no exposures of the entire member are known. On the west side of the Schoharie Valley the lower Moorehouse is fine-grained, dark-colored, and contains black chert. On the western edge of the Berne quadrangle, south of Gallupville the lower noncherty division is 6–11 feet thick and is lighter-colored and coarser-

grained than the overlying beds. This division is 13 feet thick at Berne and 16 feet thick on the east side of the quadrangle.

In the Berne quadrangle the lithology of the underlying Nedrow member is similar to the lower Moorehouse, but contains considerable light-gray chert. If the lithologic break between the cherty and noncherty limestones were used as the contact, the Nedrow and the lower division of the eastern Moorehouse would each have a constant thickness across the Berne and Albany quadrangles. In the Albany quadrangle, however, the Nedrow platyceratids are present in the higher noncherty beds; thus the Nedrow thickens from 11 to 15 feet while the lower Moorehouse thins from 16 to 11 feet. The upper Nedrow of Copeland Hill is apparently equivalent to the lowest Moorehouse farther west.

The upper division at Berne is also lighter-colored and coarser-grained than the middle division. This unit is at least 17 feet thick at Berne but thins to 10 feet on the west side of the Schoharie quadrangle. Farther west it thins more and gradually darkens. The upper division is apparently equivalent to the upper part of the black chert division of the central facies as well as the thinner upper noncherty division. East of Berne the upper division continues to thicken. It is 20 feet thick in the Onesquethaw Creek core, but two lower light-colored, noncherty beds were found that represent earlier occurrences of the upper division conditions. Farther east the upper division is nearly 30 feet thick.

While the major changes take place in the noncherty divisions, the middle division is also affected; it is thickest in the western part of the area and thins to the east. In general it is lighter-colored to the east although still darker than the noncherty units.

No exposures of the entire Moorehouse are known south of the Albany quadrangle. As far south as Kingston the member is divisible into the same divisions and may be referred to the eastern facies.

At Leeds (Coxsackie quad.) the thicknesses are: middle division (dark chert), 25+ feet; lower division (no chert), 12 feet; Nedrow member (light-colored chert) throughout, platyceratids), 43 feet. The thickness of the Nedrow is much greater at Leeds than it is to the North, possibly at the expense of the lower Moorehouse.

Farther south, in road cuts on the New York State Thruway at the Saugerties interchange, the section is more complete: middle division, 88+ feet; lower division, 12 feet; Nedrow member, approximately 34 feet. At Kingston the lower division has thinned to 7 feet, but only the lower 24 feet of the middle division is exposed. The upper division is not known south of the Coxsackie quadrangle but there is some indication that it darkens and merges with the middle division.

The eastern Moorehouse, like the central facies, contains abundant brachiopods. Some of the differences between the fossil lists of the two facies are undoubtedly due to collecting conditions, but there is little doubt that there are more specimens of more species in the central facies than in the eastern. Most of the central forms that have not been found in the east are not particularly common and are significant only as indicating a general trend. The common brachiopods are present throughout both facies.

Some differences are of more importance. The large coiled gyroconic cephalopods that are so characteristic of the central-area Moorehouse are common in the central facies of the eastern area but become less common farther east and are rare in the eastern facies. The "pteropod" *Coleolus crenatocinctum* is also characteristic in the central area. In the eastern area it is present in the central facies but has not been found east of the Richfield Springs quadrangle. The eastward changes in facies are further indicated by the distribution of *Platyceras dumosum*. This gastropod has not been found in the central area, is present or common in the upper half of the central facies of the eastern area, and is common throughout the eastern facies. This species is found most commonly in the lighter-colored rock.

The corals have not been studied in detail but are good general guides to environment. Small zaphrentids are common in the central Moorehouse, but the tabulates and large rugose corals are missing. As the rock becomes coarser-grained and lighter-colored to the east a greater variety of corals is present. They are particularly notable in the upper noncherty division. These are mostly medium-sized zaphrentids, but tabulates and other rugose corals, similar to those in the Edgecliff, are also found.

Faunal changes south of the Albany quadrangle are as interesting as those to the west. The Coxsackie and Catskill quadrangle faunas are poorly known but seem similar to those farther north. At Kingston, however, the gyroconcs reappear and are found at other places farther south. These evidently either lived or were better preserved in the finer-grained, darker phase of the Moorehouse. In addition *Platyceras dumosum* common in the Helderberg area has not been noted at Kingston or farther south. The Edgecliff type corals are not found in the southeastern area either, but this may be due to lack of exposures of the upper part of the member. In all these respects the Kingston area Moorehouse may be compared to the central facies.

Southeastern Facies

South and southeast of Kingston the Onondaga outcrop belt swings down the Rondout Valley to Ellenville, then down to the Neversink Valley and Port Jervis. In all this distance only scattered small exposures are known.

At Wawarsing 22 miles southwest of Kingston the following section is exposed in a small quarry:

	Ft.	In.
Moorehouse member:		
4. Covered		
3. Medium dark-gray limestone in beds 2–10 inches thick, some shaly beds in upper 4 feet; *Phacops* and *Odontocephalus* fragments only recognized fossils	29	
2. Thin black chert bed		2
1. Limestone, similar to above; *Levenea lenticularis*; brachiopod fragments and apparent juveniles (unidentified), very common; trilobite fragments; gyroconic cephalopod; small zaphrentid corals	20	6
Edgecliff member		

The beds probably are equivalent to the Nedrow as well as to the lower divisions of the Moorehouse (Fig. 4). They are darker than those units at Kingston, and this apparently has had an effect on the fauna, which is here sparse and atypical.

Small quarries in the Ellenville quadrangle, two at Ellenville and one at Napanoch, show 20–40 feet of medium dark-gray, noncherty limestone. The quarries are in the Moorehouse, but their position is not known in detail. The Napanoch exposure is the most extensive (40 feet) and the most fossiliferous. The following were collected:

Small zaphrentid corals	frequent
Fenestella sp.	rare
Levenea lenticularis (adults)	frequent
L. lenticularis (immature)	frequent
Choneles mucronatus	very rare
Anoplotheca acutiplicata (small)	rare
Meristella? sp. (juvenile)	rare
Tentaculites sp.	very rare
Coleolus? sp.	rare
Styliolina cf. *fissurella*	very common
Platyostoma? (juvenile?)	very rare
Odontocephalus sp.	common
Trilobite fragments	common
Ostracods	common

This is a rather sparse fauna but may be typical of the southeastern Moorehouse.

The Moorehouse is again exposed at Tristates, between the Delaware and Neversink rivers at the south end of the cemetery. An estimated 25 feet of dark-gray limestone is exposed here. The following were collected:

Ceratopora? sp.	frequent
Small zaphrentid corals	frequent
Brachiopods	rare
Platyostoma lineatum? (juvenile)	frequent
Odontocephalus selenurus	very rare
O. sp.	rare
Trilobite fragments	frequent

Kindle (1912, p. 23) found only *Phacops pipa* and *Odontocephalus* sp. at this locality.

Between the Helderberg area and Port Jervis the Moorehouse darkens considerably, and the lower division and presumably the upper is finer-grained. The color of the lower division varies from light medium gray at Berne to medium gray at Leeds and Kingston to medium dark gray at Wawarsing. The middle division is medium dark gray over most of the area but is dark gray between Ellenville and Port Jervis. The upper division is medium light gray at Berne and in the Albany quadrangle, and medium gray in the Coxsackie quadrangle; it is not known farther south.

The general stratigraphic picture seems to be correct. Some distance south in Monroe County,

TABLE 3.—MOOREHOUSE FAUNA*

Facies	Central					Eastern							
Quadrangle or locality	Winfield	Richfield Springs		Canajoharie		Schoharie to Albany			Coxsackie-Catskill			Kingston	S.E.
Division	L-M	L-M	U	L-M	U	L	M	U	L	M	U	M	
Sponge													
Hindia sp.	..	vr	..	..	..	..	..	..	..	x	..	x	..
Corals	c	c	vc	c	vc	x	c	vc	x	x	x	x	x
Bryozoans													
Fenestellate	r	x	r	x	..	r	r	x	..	x	..	..	r
Branching	..	x	..	x	..	..	..	..	..	..	..	..	..
Massive	..	vr	r	r	r	..	vr	vr	..	..	..	..	..
Botryllopora cf. *socialis*	..	..	..	vr	..	..	..	..	..	..	..	..	..
Brachiopods													
Pentagonia unisulcata	r	r	..	r	r	G	..	..	..	..	..	..	..
Isorthis propinqua	x	vr	vr	vr	..	..	vr	vr	..	..	..	..	..
Atrypa spinosa	r	x	vc	x	r	..	..	c	..	..	..	..	..
Elytha fimbriata	r	x	vr	x	..	..	vr	vr	..	..	..	..	..
Pentamerella arata	r	x	x	vr	r	r	..	r	?	..	..	x	..
Stropheodonta inequiradiata	r	c	r	r	..	G	..	..	?	..	..	x	..
S. inequistriata?	..	vr	..	..	..	..	..	..	..	..	..	..	..
S. sp. unidentified	..	..	..	..	..	..	vr	..	..	r	..	..	..
Protoleptostrophia perplana	vr	r	..	..	..	r	..	?	..	..	..	c	..
Leptaena rhomboidalis	x	c	x	x	..	x	vr	c	x	r	..	x	J?
Schuchertella pandora	vc	c	..	c	..	x	r	r	..	?	..	c	..
Atrypa reticularis	vc	vc	vc	c	c	c	vc	vc	c	c	r	vc	..
"Spirifer" raricostus	r	r	vr	r	..	c	r	r	x	..	c	r	..
Levenea lenticularis	vc	vc	x	c	..	r	x	x	x	..	x	vc	x
Choneles mucronatus	r	c	x	?	..	..	vr	c	..	x	..	..	vr
C. hemisphericus?	..	r	..	..	..	..	..	..	..	..	..	..	..
Meristella doris	..	r	..	?	..	..	..	..	..	..	..	..	..
Cymostrophia patersoni	..	r	vr	..	..	..	..	..	..	..	..	..	..
Stropheodonta demissa	..	vr	r	..	..	..	..	..	..	..	..	..	..
Choneles deflectus	..	vr	..	r	..	..	..	..	..	..	..	..	..
Strophonella ampla	..	vr	..	vr	..	?	..	..	..	..	..	..	..
Nucleospira concinna	..	r	..	r	..	..	..	?	..	..	..	..	..
"Spirifer" varicosus	..	vr	..	..	..	G	..	?	..	..	..	..	..
Rhipidomella sp.	..	r	..	r	r	x	vr	vr	..	..	..	..	..
"Spirifer" duodenarius	..	r	r	x	..	c	r	c	..	..	..	?	..
Athyris spiriferoides	..	r	..	..	..	..	..	r	..	..	..	..	..
Camarotoechia billingsi	..	vr	..	..	..	..	..	vr	..	..	..	..	..
Megastrophia hemisphaerica (= *concava?*)	..	r	vr	vr	..	r	..	?	..	r	r	..	..
Productella navicella	..	r	..	?	..	..	..	vr	..	..	..	x	..
Coelospira camilla	?	x	r	x	c	..	c	x	..	..	..	r	..
Anoplotheca acutiplicata	..	r	..	c[1]	..	..	..	..	..	..	..	..	J
Pholidostrophia nacrea?	..	..	vr	..	..	..	..	..	..	..	..	..	..
Paraspirifer acuminatus	..	..	vr	..	..	..	..	..	..	..	..	..	..
Camarotoechia tethys	..	..	vr	vr	..	..	..	..	..	..	r	..	..
Athyris cf. *vitata*	..	..	..	vr	..	..	..	..	..	..	..	..	..
"Spirifer" macrus	..	..	..	..	..	r	..	..	..	..	..	..	..
Fimbrispirifer divaricatus	..	..	..	..	..	..	?	..	..	..	..	..	..
Meristella? sp. (juveniles?)	..	..	..	..	..	..	..	..	..	x	..	r	x
Levenea lenticularis? (juveniles?)	..	..	..	..	..	..	..	..	..	..	..	vc	x

TABLE 3.—*Continued*

Facies	Central					Eastern							
Quadrangle or locality	Winfield	Richfield Springs		Canajoharie		Schoharie to Albany			Coxsackie-Catskill			Kingston	S.E.
Division	L-M	L-M	U	L-M	U	L	M	U	L	M	U	M	
Gastropods and "pteropods"													
Coleolus crenatocinctum	vr	r	..	?	..	..	..	..	..	..	..	..	..
"Pleurotomaria" sp. A.	vr	..	..	..	..	..	..	?	..	..	..	c	..
Hyolithes cf. *striatus*	..	vr	..	..	..	..	..	..	..	..	..	..	..
Styliolina cf. *fissurella*	..	x	..	..	..	..	..	..	..	..	..	..	..
Euomphalus decewi	..	vr	..	vr	..	..	..	..	..	..	..	..	..
Loxonema sp.	..	r	..	vr	..	..	..	..	..	..	..	..	..
Platyostoma turbinatum	..	vr	..	r	..	..	..	vr	..	..	..	..	..
Platyceras carinatum	..	vr	..	?	..	..	..	vr	..	..	..	..	..
P. sp. unidentified (not *P. dumosum*)	..	vr	..	..	r	..	..	..	x	..	..	..	..
P. dumosum	..	c	r	c	r	c	c	r	r	c	..	..	..
Platyostoma lineatum	..	x	..	c	..	..	..	..	..	r	..	r	J
Platyceras fornicatum	..	..	..	..	..	..	..	..	r	..	..	..	..
Platyostoma sp. (juveniles)	..	..	..	..	..	..	..	..	..	..	..	..	x
Cephalopods													
Goldringia citum?	..	vr	..	..	..	..	..	..	..	..	..	..	..
G. trivolvis	..	vr	..	..	..	..	..	..	..	..	..	..	..
Other gyrocones	c	x	..	x	..	r	vr	vr	..	..	..	c	vr
Striacoceras typum	..	vr	..	..	..	..	..	..	..	..	..	..	..
Other orthocones	..	..	..	..	..	r	..	..	..	..	..	..	..
Pelecypod													
Aviculopecten ignotus	..	vr	..	..	..	..	..	..	..	..	..	..	..
Paracyclas cf. *lirata*	..	..	..	vr	..	..	..	..	..	..	..	..	..
Trilobites													
Unidentified (fragmental)	x	c	x	c	..	x	x	r	..	..	..	x	c
Phacops sp.	x	c	x	x	r	..	vr	r	r	c	r	x	x
"Proetus" sp.	..	vr	vr	..	..	..	..	vr	..	..	..	r	..
Odontocephalus bifidus	..	vr	..	vr	..	..	..	..	..	..	..	..	..
Phacops pipa	..	vr	vr	x	..	..	..	..	..	..	..	..	..
Odontocephalus selenurus	..	vr	..	..	..	..	..	r	..	..	..	r	vr
O. sp.	..	c	vr	r	..	r	..	r	r	r	..	x	x
Ostracods	..	x	..	x	..	..	..	..	..	..	..	c	x
Crinoids													
Eutaxocrinus? sp.	..	vr	..	..	..	..	..	..	..	..	..	..	..
Dolatocrinus marshi var. *glaber*	..	..	..	vr	..	..	..	..	..	..	..	..	..
Schultzicrinus? sp.	..	..	..	vr	..	..	..	..	..	..	..	..	..
Blastoid													
Nucleocrinus verneuili?	..	..	..	vr	..	..	..	..	..	..	..	..	..
Fish teeth	r	r	r	vr	..	..	..	..	..	..	..	..	..

* *See* Table 1 for symbols

[1] Locally

J. Rare juveniles

G. Reported by Goldring (1935, p. 148) from quarry known to be in this unit

L-M. Lower and middle (dark chert) Moorehouse

L. Lower (no chert) Moorehouse

M. Middle (dark chert) Moorehouse

U. Upper (no chert) Moorehouse

TABLE 4.—UPPERMOST MOOREHOUSE FAUNA*

Locality	Lawyersville	Thompsons Lake	Kaaterskill
Corals			
Small zaphrentids	x	..	c
Bryozoans			
Fenestellate	..	r	..
Massive	c	r	..
Brachiopods			
Levenea lenticularis	c	r	c
Pentamerella arata	..	r	?
Protoleptostrophia perplana	x	..	..
Leptaena rhomboidalis	r	r	r
Schuchertella pandora	..	..	x
Chonostrophia reversa	c	..	c
Choneles deflectus	x	..	..
C. lineatus	..	..	x
C. mucronatus	?	c	?
Atrypa reticularis	vc	c	..
Coelospira camilla	x	r	vc
Cyrtina hamiltonensis	r	..	..
Elytha fimbriata	r	..	..
"Spirifer" duodenarius	?	..	r
"Sp." varicosus	..	?	x
Gastropod			
Platyostoma lineatum	?	..	?
Trilobites			
Odontocephalus selenurus	..	x	r
O. sp.	..	r	x
"Proetus" sp.	?	..	..

* *See* Table 1 for symbols

Pennsylvania, the Onondaga is "a massive, dark- or blue-gray rock replete with chert occurring usually as dark bands or nodules. . . . The material [chert] appears to be most abundant in the middle 50 to 100 feet, while the highest and lowest parts are sometimes nearly chert free" (Willard, 1939, p. 144). The formation here is about 200 feet thick, and the description might well fit the Port Jervis exposures if they were more extensive.

There is little chert in the Moorehouse outcrops south of Kingston. The few exposures may all be in the noncherty divisions, or the member may be relatively chert free in this area.

The physical changes are accompanied by faunal changes. The differences southward are first noted in the middle Moorehouse at Kingston (*see* Table 3). Here the fauna is rather typically eastern facies Moorehouse except that *Pleurotomaria* sp. and gyroconic cephalopods, typical of the central Moorehouse, are present. Also, apparent juveniles of *Levenea lenticularis* and *Meristella*? sp. are common. These are rather characteristic of the southeastern Moorehouse facies.

Farther south at Wawarsing, Napanoch, and Port Jervis the fauna consists primarily of undersized or juvenile brachiopods and gastropods and normal trilobites and corals. The undersized benthonic forms may indicate an oxygen-poor environment. The dark gray lithology fits this interpretation. The trilobites were probably pelagic as were the "pteropods" (*Hyolithes*, *Tentaculites*, and *Coleolus*?) and the one cephalopod. The corals are anomalous, however. These are similar to the small zaphrentids that are common everywhere in the medium- to dark-gray Moorehouse. They were apparently able to tolerate the conditions as adults, although they are not as common here as they are farther north and west.

Upper Contact

In the Richfield Springs and Canajoharie quadrangles the Moorehouse is overlain by the Seneca member. East of Cherry Valley the Seneca grades laterally into the Union Springs black shale, and the Moorehouse is overlain by that member. The contact, observed in four places, seems to be gradational.

In a road cut and ditch exposure on the west side of Highway 145, 1.15 miles north of Lawyersville (Richmondville quad.), the uppermost Moorehouse is overlain by the black shale. The limestone is darker gray than is usual for the upper noncherty division and is quite fossiliferous (Table 4).

In a small stream behind the old hotel at Thompsons Lake (Berne quad.), the upper 1 foot of the Onondaga is dark gray and is overlain by 3 or 4 feet of black shale with a few thin grayish-black limestone beds. The fauna of the uppermost Onondaga is listed on Table 4. The higher, darker limestones are unfossiliferous and are referred to the Union Springs. In

Onesquethaw Creek (Albany quad.) Goldring (1943, p. 243) reported a similar 3-foot transition zone from limestone to black shale.

Just southwest of Catskill the contact is again exposed in the Kaaterskill, where Route 23A crosses it. Chadwick (1927, p. 160; 1944, p. 103) described a "very distinct erosion surface" at the top of the Onondaga here and stated that it "appears to dispose finally of the theory of 'contemporaneous overlap' by the Marcellus black shale." He based this on the presence of a thin calcarenite at the base of the black shale. The bed contains "crinoidal fragments... and comminuted fish remains with an occasional brachiopod shell seemingly reworked from the limestone beneath." This certainly represents a break of some sort, but the limestone is dark gray in contrast to the medium gray which is typical for the upper Moorehouse in this area. A gradual change in late Onondaga time is indicated, and the break is probably minor as suggested by Cooper (1930, p. 123).

Fauna

The known Moorehouse fauna is indicated in Table 3. Identifications are listed for each facies and division, and geographical variations are shown insofar as possible. The uppermost Moorehouse fauna is listed separately (Table 4) for easy comparison with the Seneca list.

Seneca Member

The Seneca member was named by Vanuxem (1839, p. 275–278) from exposures in Seneca County (Geneva quad.). The entire member is exposed at Union Springs, Cayuga County (Auburn quad.), but no complete sections are known in Onondaga County, the type locality for the other members and the formation. The eastward extent of the Seneca was discussed by Oliver (1954, p. 629–631, 642), and additional data on the member in the eastern area are given here.

The section at Union Springs is as follows:

	Ft.	In.
Cherry Valley limestone (Marcellus formation)		
Union Springs black shale (Marcellus formation):		
6. Black shale with 5 or 6 beds of bituminous limestone	13	
Seneca limestone (Onondaga formation):		
5. Zone L; dark limestone beds, 10–12 inches thick, separated by 1- to 10-inch beds of black shale; corresponding limestone beds in near-by section have Onondaga fauna	5	10
4. Zone K; series of dark-gray limestone beds, 2–12 inches thick; *Chonostrophia reversa* (common), *Chonetes lineatus* (frequent), other fossils rare	8	9
3. Zone J (Pink *Chonetes* zone); thin-bedded limestone composed almost entirely of the shells of *Chonetes lineatus*; other fossils very rare	3	10
2. Zone I; medium dark-gray limestone similar to the upper Moorehouse; but has smaller number of species and is the first zone where *Chonetes lineatus* is common	6	6
1. Zone H; Tioga bentonite		6
Moorehouse member		

The Tioga bentonite marks a faunal break as well as a prominent lithologic horizon and defines the base of the Seneca as essentially a time plane.

At Stockbridge Falls, Morrisville quadrangle, the section is as follows:

	Ft.	In.
Cherry Valley limestone		
Union Springs black shale:		
5. Black shale with 14 or more dark limestone beds 1 to 5 inches thick in the upper 17 feet	27	
Seneca limestone:		
4. Zone K; thin-bedded, dark-gray limestone; *Chonostrophia reversa* is common		6
3. Zone J (Pink *Chonetes* zone); thin-bedded, dark-gray limestone with abundant *Chonetes lineatus* and few other forms	3	3
2. Zone I; medium dark-gray limestone with *Chonetes lineatus*, *C. mucronatus*, and few others	6–7	
1. Zone H, Tioga bentonite; not positively identified, but 2–4 inch deeply weathered zone is almost certainly this bed		4
Moorehouse member		

This section is identical to that at Union Springs, 55 miles west, except that the black shale contact is lower, cutting out zone L and all but the lower 6 inches of zone K. Yet at both localities there is every indication that the contact is gradational. From zone I upward the beds darken gradually, and black shale and limestone interfinger up to the Cherry Valley member. In this transition the varied Moorehouse fauna is replaced by an abundance of two species of *Chonetes* and *Chonostrophia*.

Only three exposures of the Seneca are known farther east. The member is exposed in two new road cuts 2 miles northeast of Cherry Valley (Canajoharie quadrangle). One small cut shows the black shale contact and 3–4 feet of the Seneca; half a mile east the whole member, 6 feet thick, is exposed, but the black shale has been removed. The Tioga bentonite is 3–8 inches thick and in weathering forms a prominent re-entrant at the base of the member.

One mile south of Cherry Valley the uppermost 3 feet of the Onondaga and most of the Union Springs and Cherry Valley members are exposed. The Onondaga formation was cored there in the summer of 1952 by the State College of Ceramics, and the following section is a composite from the core and exposure:

	Ft.	In.
Cherry Valley limestone		
Union Springs black shale:		
3. Black shale, lower 6 feet exposed with no limestone beds; middle part covered; upper few feet exposed with few limestone beds	27–	30
Seneca limestone:		
2. Zone I; medium dark-gray, fine- to medium-coarse-grained limestone; a few of a variety of brachiopods	6	
1. Zone H, Tioga bentonite (C. S. Ross, *in* Oliver, 1954, p. 630)	3	
Moorehouse member		

In the 45 miles between Stockbridge Falls and Cherry Valley the Union Springs contact continues to descend so that zones J and K, in addition to zone L, are missing at Cherry Valley. A gradational contact is again indicated. That the lateral change from limestone to black shale is a facies change is further supported by the fact that *Chonetes lineatus* was not found in the Seneca at Cherry Valley. This diagnostic Seneca species decreases in number upward as the black shale becomes predominant, and it also is less abundant eastward toward the limit of Seneca deposition.

Farther east the Union Springs rests directly on the Moorehouse, and an unknown thickness of Moorehouse at Cherry Valley must be equivalent to black shale farther east. Commonly the Moorehouse-Union Springs contact is gradational.

TABLE 5.—SENECA FAUNA*

Locality	Stockbridge Falls			Cherry Valley area
Zone	I	J	K	I
Brachiopods				
Levenea lenticularis	..	x	x	x
Pentamerella arata	..	..	..	vr
Protoleptostrophia perplana	..	..	r	..
Leptaena rhomboidalis	..	..	..	x
Schuchertella pandora	..	..	..	r
Chonostrophia reversa	..	x	vc	..
Chonetes lineatus	x	vvc	c	..
C. mucronatus	c	..	r	x
Atrypa reticularis	..	..	..	vc
A. spinosa	..	..	..	x
Coelspira camilla	r	..	..	x
"Spirifer" duodenarius	..	..	..	vr
"Sp." grieri?	..	..	..	r
"Sp." varicosus	..	..	r	..
Gastropods				
Platyostoma? sp.	..	..	..	r
Platyceras erectum	..	..	..	vr
Trilobites unidentified	..	..	r	..
Ostracods	..	?	x	..

* *See* Table 1 for symbols

From Union Springs to Cherry Valley the Tioga bentonite-Cherry Valley limestone interval is remarkably uniform. At Union Springs the intervening thickness is 38 feet; at Stockbridge Falls it is 37–38 feet; and at Cherry Valley it is 33–36 feet. Farther east the Union Springs member thickens at an increased rate. This is due partly to the fact that it is equivalent to the uppermost Moorehouse, as well as the Seneca, but probably more important is the fact that the rate of deposition of the black shale exceeded that of the limestone.

Where the Seneca is missing in the area east of Cherry Valley, the bentonite must be in the black shale. This has been recognized in Pennsylvania where the bentonite in western wells is as much as 30 feet below the contact and farther east is at or just above the contact (Fettke, 1952).

The fauna of the Seneca member is listed by zones at Stockbridge Falls and in the Cherry Valley area (Table 5).

Distribution of Chert

In most of the area under consideration chert can be used to divide the Onondaga into five lithologic units (Fig. 3). Lower, middle and upper series of noncherty beds are separated by a lower series of beds with light-colored chert and an upper series with dark chert. It is interesting to note the relationship of these 5 divisions to the 4 members.

The lower noncherty beds are everywhere Edgecliff. In the central area, and as far east as the Canajoharie quadrangle, the lower, light-colored chert is restricted to the Edgecliff, and the middle noncherty beds are Nedrow. The lowermost occurrence of the dark chert in this area is in the upper Nedrow, and in the central area it persists through the Moorehouse into the Seneca. Chert has not been found in the Seneca at Stockbridge Falls (Morrisville quad.) or farther east, and in the Richfield Springs quadrangle the uppermost Moorehouse is also noncherty.

In the Schoharie and Berne quadrangles the light-colored chert is present in the Nedrow member, so the upper Edgecliff (also with light-colored chert) and Nedrow can be differentiated only on a faunal basis. The light-colored chert generally persists to the top of the Nedrow, and the middle noncherty beds are lower Moorehouse. The upper noncherty beds thicken east of the Richfield Springs quadrangle, and the eastern Moorehouse facies can be divided into three subequal parts.

This condition prevails in the Albany quadrangle and as far south as Kingston (Rosendale quad.). Farther south at Wawarsing the lower cherty beds are again limited to the Edgecliff, and all higher divisions are Moorehouse. South of Wawarsing the section is poorly known. Only scattered nodules of chert were found in the Edgecliff at Wawarsing, and none was seen at Port Jervis.

The color of the chert is closely related to the color of the limestone. The upper chert series is contained in the darker facies of the Moorehouse. This chert ranges in color from nearly black to medium gray as the limestone becomes lighter-colored eastward. Both limestone and chert are darker again south of Kingston. In contrast, the lower chert is almost always light gray, reflecting the color of the Edgecliff and eastern Nedrow limestones. As the Edgecliff darkens in the southeastern facies the chert does also and is medium gray at Wawarsing.

The chert reflects the lithologic facies and, therefore, the depositional environment of the limestone. The upper, dark chert beds are present throughout the Moorehouse in the Richfield Springs quadrangle, and no subdivision has been established. Farther east the member can be divided into the three lithologic units, and the distribution of fossils tends to support such a division.

Onondaga Fauna

Corals

Corals are the most important guides to the depositional environment of the Onondaga limestone. They show considerable variations with lithology and apparently were affected by comparatively slight changes in environment.

The Edgecliff contains an abundance of many different types of corals. The bioherm and normal facies each have their own rugose faunas, while the same tabulates are common to both. In the darker and finer-grained facies of the Edgecliff, the corals are uncommon. Typical Edgecliff corals are scarce in the lower (C1) part of the member in the Richfield Springs quadrangle and they gradually become rare to the south in the southeastern facies.

In the central area, the shaly Nedrow (zone D) is characterized by a low turbinate form of *Heliophyllum halli* and by *Amplexiphyllum* cf. *hamiltoniae*. Both are common in the calcareous shales of the younger Hamilton group. As the Nedrow becomes less shaly eastward these corals become less common, but *A.* cf. *hamiltoniae* has been found as far east as the Schoharie quadrangle and *H. halli* is known through-

out the eastern and southeastern extent of the member.

Small zaphrentids are common in all of the medium and medium dark-gray, fine-grained limestones. These are present throughout the Moorehouse and in the darker, southeastern facies of the Nedrow and Edgecliff.

In the lighter-colored, eastern Moorehouse larger zaphrentids, such as *Heterophrentis prolifica*, are fairly common, and in the upper, noncherty division a few cystimorphs, bethanyphyllids, and tabulates, reminiscent of the Edgecliff, are found.

Brachiopods

Brachiopods are present in all subdivisions of the formation, but only a few of them are restricted (Table 6). Of 47 species definitely identified in the eastern area, only 7 seem to be limited to a single member. All of these are rare in the eastern area, and only one is significant. *Paraspirifer accuminatus* is present in the upper Onondaga in western New York and has been found in the uppermost Moorehouse in the Richfield Springs quadrangle. It is probable that this species is limited to late-Moorehouse and post-Moorehouse deposits. Two other species, *Chonetes lineatus* and *Chonostrophia reversa*, found only in the uppermost Moorehouse and Seneca members, also indicate late-Onondaga deposits.

A few species seem characteristic of the Moorehouse and Seneca members although present in lower units also. *Chonetes mucronatus*, *Athyris spiriferoides*, *"Spirifer" varicosus*, *Elytha fimbriata*, *Coelospira camilla*, *Productella navicella*, *Leptostrophia perplana*, and *Levenea lenticularis* belong to such a group. These species and a few others may form an essentially post-Edgecliff fauna, or their distribution may be due to environmental conditions.

An "early Onondaga" fauna reported by Stauffer (1915, p. 15–20) from southwestern Ontario and by Oliver (1954, p. 626, 632) (Zone B) from western New York may exist also. *Amphigenia elongata*, *Centronella glansfagea*, and others characterize this fauna. These two species are abundant in these western basal beds and present in the Edgecliff elsewhere, but both are known also from the Moorehouse.

Meristella nasuta, *M. scitula*, and *"Spirifer" raricostus* are more typical of the Edgecliff but are known in higher members. *"Spirifer" raricostus* is fairly common in the lighter-colored parts of the eastern Moorehouse. The distribution of this and other species seems to parallel changes in lithology, and they were probably environmentally controlled.

Mollusks

Platyceratid gastropods referable to the "genera" *Platyostoma*, *Platyceras*, and *Orthonychia* characterize the Nedrow, but few species are restricted to any member. Table 7 lists numerous Edgecliff platyceratids in eastern and western New York, but few in the central area. Almost all the western forms are from the reef facies, and their presence in the eastern area is probably related to the abundance of reefs there also. No reefs are known in the central area, and platyceratids are notably absent from the Edgecliff.

Platyceras dumosum is common in the eastern Moorehouse and present in the eastern Nedrow but rare elsewhere. This species apparently preferred the environment represented by the somewhat lighter-colored and coarser-grained eastern lithologies and is the most common gastropod in that facies of the Moorehouse.

Different gastropods are present in the central Moorehouse. *Euomphalus* sp., *"Pleurotomaria"* sp. A., *Loxonema* sp., and *Coleolus crenatocinctum* (a "pteropod") are most notable. None of these is common in eastern New York, but in central New York they and *Bellerophon* sp. are common and characteristic Moorehouse and Seneca types (Oliver, 1954, p. 628).

It seems likely that the distribution of the gastropods was controlled primarily by the depositional environment. The Nedrow has not been recognized in the western area, and it does not occur south of Kingston in the southeastern area. In both areas the Nedrow is represented by dark limestones with an essentially Moorehouse fauna and no platyceratids. The Moorehouse gastropods are found in the medium-gray, fine-grained facies and become less common eastward as this grades into somewhat lighter-colored, coarser-grained rock.

Large gyroconic nautiloid cephalopods such as *Halloceras undulatum* and *Goldringia* sp. are locally common in the Moorehouse and are

TABLE 6.—DISTRIBUTION OF BRACHIOPODS IN THE ONONDAGA LIMESTONE*

Member	Edgecliff			Nedrow			Moorehouse			Seneca		
Area	E	C	W	E	C	W	E	C	W	E	C	W
"Spirifer" manni	x	..	..	..	..	..	..	..	..	..	..	..
"Terebratula" lens	vr	..	..	..	..	..	..	..	..	..	..	..
Meristella scitula	vr	..	x	vr	..	..	..	..	..	..	..	..
"Spirifer" subumbonus	..	..	vr	vr	..	..	..	..	..	..	..	..
Rhipidomella sp.	vr	..	vr	..	..	..	x	..	vr	..	..	..
Cymostrophia patersoni	vr	..	..	vr	..	..	vr	..	r	..	..	..
Megastrophia hemisphaerica (= concava?)	vr	..	vr	vr	vr	..	x	r	r	..	..	..
Fimbrispirifer divaricatus	r	..	..	..	..	..	vr	..	vr	..	..	..
"Spirifer" raricostus	x	x	r	c	x	..	c	x	r	..	..	..
Ambocoelia umbonata	vr	..	..	..	..	..	..	..	vr	..	..	..
Amphigenia elongata	r	vr	x	..	..	..	..	..	vr	..	..	..
Centronella glansfagea	..	..	x	?	..	..	..	..	vr	..	..	..
Levenea lenticularis	r	?	r	x	x	vr	vc	x	vc	c	c	c
Isorthis propinqua	vr	..	..	..	..	..	x	x	r	..	..	vr
Pentamerella arata	r	r	r	x	vr	..	x	x	vr	vr	..	vr
Protoleptostrophia perplana	r	..	r	..	..	..	x	c	c	vr	..	vr
Stropheodonta demissa	vr	..	..	..	..	..	vr	..	r	..	..	vr
S. inequiradiata	vr	vr	vr	vr	vr	..	r	x	x	..	..	vr
Leptaena rhomboidalis	r	r	c	..	r	..	c	x	x	vr	vr	x
Schuchertella pandora	x	r	c	vr	vr	vr	c	c	c	r	r	x
Chonetes deflectus	?	vr	..	..	..	..	vr	..	r	..	..	x
C. mucronolus	r	..	..	r	r	vr	c	c	vc	c	c	c
Camarotoechia tethys	x	..	..	..	vr	..	vr	..	vr	..	..	x
Atrypa reticularis	c	r	x	c	c	..	vc	c	vc	x	vr	c
Coelospira camilla	vr	vr	..	vr	r	vr	x	vr	c	r	r	c
Anoplotheca acutiplicata	r	..	..	..	x	..	r	c	x	..	vr	vr
Elytha fimbriata	r	r	vr	vr	..	..	x	x	c	..	..	r
"Spirifer" duodenarius	r	vr	x	vr	..	..	x	?	r	vr	..	x
"Sp." grieri	vr	..	..	vr	..	..	..	..	vr	vr	..	..
Meristella nasuta	x	r	r	vr	r	..	vr	?	r	..	..	vr
Pentagonia unisulcata	r	..	vr	c	vr	..	x	r	vr	..	..	r
Meristella doris	vr	..	?	?	..	..	vr	r	r	..	..	vr
"Spirifer" disparalis	..	..	..	vr	..	..	..	..	..	..	..	..
Lingula cf. *desiderata*	..	..	..	vr	vr	..	..	r	r	..	..	..
Productella navicella	..	..	..	..	vr	..	r	x	r	..	..	..
Nucleospira concinna	..	..	..	vr	..	..	r	..	r	..	..	..
Strophonella ampla	..	..	..	r	..	..	r	..	..	..	..	vr
Atrypa spinosa	..	..	..	r	..	..	c	r	r	x	vr	c
"Discina" sp.	..	..	..	?	..	..	..	vr	vr	..	..	..
Cyrtina hamiltonensis	..	..	..	..	..	..	vr	..	..	..	..	..
Paraspirifer acuminatus	..	..	..	..	..	..	vr	..	r	..	..	..
"Spirifer" macrus	..	..	..	..	..	..	vr	..	vr	..	..	..
Camarotoechia billingsi	..	..	..	..	..	..	vr	..	r	..	..	vr
"Spirifer" varicosus	..	..	..	?	..	..	vr	..	x	vr	..	..
Athyris spiriferoides	?	..	..	..	..	..	r	c	r	..	vr	r
Chonostrophia reversa	..	..	..	..	..	..	u	..	..	vc	c	x
Chonetes lineatus	..	..	..	..	..	..	u	u	..	vc	vc	c

* *See* Table 1 for symbols
u. Upper part only
E. Eastern and southeastern areas
C. Central area
W. Western area

characteristic of the central facies. These are less common in the east. Only a few specimens have been found in other members.

Other cephalopods are rare. A few orthocones have been found, mostly in the Moorehouse, and four goniatite specimens (*Tornoceras* cf. *buttsi*) are known from the upper Nedrow in the Richfield Springs quadrangle. The latter are of considerable interest because they represent some of the oldest goniatites found in North America.

TABLE 7.—DISTRIBUTION OF GASTROPODS IN THE ONONDAGA LIMESTONE*

Member	Edgecliff			Nedrow			Moorehouse			Seneca		
Area	E	C	W	E	C	W	E	C	W	E	C	W
Platyostoma lineatum	r	..	x	x	c	..	x	r	r	..	..	x
P. turbinatum	x	..	r	c	c	..	vr	..	vr	..	..	..
P. turbinatum var. *cochleatum*	vr	..	..	..	..	..	..	..	..	..	..	..
P. sp.	r	..	x	c	c	..	x	..	..	vr	..	..
Platyceras argo	vr	..	vr	vr	..	..	..	..	..	..	..	..
P. carinatum	vr	..	vr	x	r	..	vr	..	..	..	..	r
P. cf. *crassum*	..	..	..	vr	..	..	..	..	..	..	..	..
P. dumosum	vr	..	r	x	x	..	c	..	..	..	..	..
P. cf. *echinatum*	..	..	..	vr	..	..	..	..	..	..	..	..
P. erectum	r	..	r	?	r	..	..	..	..	..	..	..
P. fornicatum	..	..	..	vr	x	..	vr	..	..	..	..	..
P. nodosum?	..	..	..	vr	..	..	..	..	..	..	..	..
P. rictum	vr	..	..	..	x	..	..	..	..	..	..	..
P. cf. *undatum*	vr	..	..	..	..	..	..	..	..	..	..	..
P. sp. unidentified (not *P. dumosum*)	r	vr	r	vc	vc	..	r	..	..	..	..	..
Orthonychia conicum	..	..	..	r	x	..	..	..	..	..	..	..
O. dentalium	..	..	..	r	..	..	..	..	..	..	..	..
O. sp.	r	..	..	r	x	..	..	..	..	..	..	..
"Pleurotomaria" plena	vr	..	..	..	..	..	..	..	..	..	..	..
"P." sp.	vr	..	..	vr	..	..	..	..	..	..	..	..
"P." sp. *A.*	..	..	..	..	..	..	r	c	vr	..	..	..
Euomphalus sp.	..	..	..	..	..	..	r	vr	vr	..	..	..
Loxonema sp.	..	..	..	..	..	..	r	c	..	..	x	..
Coleolus crenatocinctum	..	..	..	..	..	..	r	vc	..	..	c	vr
Hyolithes cf. *striatus*	..	..	..	..	..	..	vr	..	..	..	..	..
Styliolina cf. *fissurella*	..	..	..	vr	..	..	x	x	r	..	..	..

* *See* Table 1 for symbols
E. Eastern and southeastern areas
C. Central area
W. Western area

Trilobites

Trilobites are common in all members but the Seneca (Table 8). However, comparatively few specimens are found sufficiently intact for specific identification. The known distribution of the species and the relative abundances of the genera are shown in Table 8. The species ranges are based on too few specimens to be significant. The paucity of trilobites in the Seneca member is probably due to environmental conditions.

Others

Crinoids were abundant in the Onondaga seas, but were rarely preserved as entire skeletons. Their significance in the Edgecliff has been discussed. Bryozoans are common throughout the formation, but systematic work must precede stratigraphic work on these forms. Ostracods are also common, but are hard to extract from the matrix and usually cannot be

identified in place. Sponge spicules are fairly common in the central Moorehouse, but have not been searched for in the east. The sponge *Hindia* sp. is known from the western Edgecliff, the eastern and southeastern Nedrow, and shallow seaway, with generally well agitated water providing optimum conditions for the growth of large numbers of sessile corals and crinoids. The lower Edgecliff (C1) in the Richfield Springs and adjacent quadrangles

TABLE 8.—DISTRIBUTION OF TRILOBITES IN THE ONONDAGA LIMESTONE*

Member	Edgecliff			Nedrow			Moorehouse			Seneca		
Area	E	C	W	E	C	W	E	C	W	E	C	W
Odontocephalus bifidus	..	..	..	..	..	..	vr	..	..	..	..	..
O. selenurus	..	..	..	vr	..	..	x	..	..	..	..	..
O. sp.	x	..	..	r	x	..	x	c	x	..	x	x
Euarges contusus	vr	..	..	..	..	..	..	..	..	..	..	..
Phacops cristata	vr	..	..	..	..	..	..	..	..	..	..	..
P. pipa	vr	..	..	vr	..	..	r	..	..	..	..	..
P. sp.	r	vr	x	c	c	..	c	c	x	..	..	..
Dechenella clara	..	..	..	..	..	..	vr	..	..	..	..	..
D. halli	vr	..	..	vr	..	..	..	..	..	..	..	..
D. cf. *macrocephala*	vr	..	..	..	..	..	..	..	..	..	..	..
D. microgemma	vr	..	..	vr	..	..	..	..	..	..	..	..
"*Proetus*" sp.	r	..	..	r	..	..	r	..	..	..	..	..
"*Cyphaspis*" cf. *craspedota*	..	..	..	vr	..	..	..	..	..	..	..	..
"*C.*" sp.	vr	..	..	..	..	..	..	..	..	..	..	..

* *See* Table 1 for symbols
E. Eastern and southeastern areas
C. Central area
W. Western area

the central and eastern Moorehouse, but further study may show it to be even more widespread. Blastoids and pelecypods are rare and were not an important part of the Onondaga biocoenose.

CONCLUSIONS

Although for half a century the Onondaga limestone has been considered a single lithologic unit, it is now recognized as a complex of zones, members, and facies, each with its own peculiarities of lithology and fauna. In central New York, Oliver (1954) recognized a sequence of 11 zones or series of beds, all limestone, but varying in the nature of their impurities and faunas. East and west of the central area various facies changes were recognized. The eastern and southeastern changes have been studied in detail for this paper, and it is evident that a great variety of environments is represented, in part sequential, but primarily overlapping in time.

The Edgecliff was deposited in a widespread, probably marks a broad depression on the floor of the sea in which a higher percentage of argillaceous material accumulated. A few of the same corals lived there, but not in abundance. Perhaps all the corals in the C1 facies were introduced, the conditions being sufficient for growth but not for proliferation. In surrounding areas, however, numerous corals and crinoids nearly covered the sea bottom at times (C2 environment). Later, the C1 conditions were succeeded by an environment more favorable to coral-crinoid growth and the C2 environment was very widespread.

Toward the southeastern shore line, however, considerable silt and mud accumulated with the limestone, forming the Schoharie formation. This gave way to limestone in late Edgecliff times, but conditions were not favorable for the corals, and only the characteristic large crinoid columnals identify the deposit.

Locally, in the area of typical Edgecliff development, small patch reefs formed. These started growing at various times and met with

varying success. Several of them were built as much as 50 feet above the surrounding sedimentation level and probably were within the zone of wave erosion as evidenced by the flanking beds. There is no obvious pattern to the distribution of the reefs. None are known in the southeastern facies where conditions for coral growth were not good, but within the area of normal Edgecliff development the initiation of reef growth may have been a chance occurrence. Colonial rugose corals were the frame builders, and the presence of tabulates, solitary rugose corals, crinoids, and a variety of vagrant benthonic animals indicate an environment analogous to the shelf patch reefs of today.

The significance of the Edgecliff chert is uncertain. Laird (1935), concluded that the chert in Ontario was "penecontemporaneous." He gave evidence to indicate that the chert nodules were not deposited with the limestone and suggested that organic decay started the precipitation of colloidal silica soon after burial but before consolidation (1935, p. 289). The chert distribution is not random, but in places chert is abundant throughout the Edgecliff and at other places, absent. Where chert is present the corals are never as abundant as they commonly are where it is absent, and it seems evident that either the conditions which produced the chert, or the chert itself, was a factor limiting coral growth.

Nedrow conditions were initiated by an influx of mud, slight in the Helderberg area, but sufficient to change drastically the environment in the central area. At Richfield Springs the effect is marked by the thinner, argillaceous, lower Nedrow beds. These beds can be traced eastward to the Helderbergs, but no break is evident to the southeast at Leeds. The effect on the environment was marked. The Edgecliff corals are absent except in the east where the change was not so great. Corals on the larger reefs were in a more favorable position, and growth may have continued longer. These also were buried under the more argillaceous, post-Edgecliff deposits.

The combined Nedrow-Moorehouse members are thinner and less pure in the central area than in the east. Apparently the water was deeper in central New York and the rate of accumulation of mud relative to calcium carbonate was higher, even though the source area was farther away.

In the muddier early Nedrow seas, platyceratid gastropods became the most characteristic animals that have left a record. They are to be noted more for their variety than for the abundance of any one particular type, and many of the so-called species may be environmental variants or formae.

Brachiopods also became abundant under the Nedrow conditions. Perhaps the most important factor in their environment was the lack of corals and crinoids. There is no obvious reason why the Edgecliff conditions would not have been suitable for brachiopods. Certain types are fairly common in that member, but everywhere they are overshadowed by the abundant corals.

The general influx of mud was sufficient to terminate Edgecliff conditions over large areas, but the new conditions soon changed. As the Nedrow deposits became less argillaceous the platyceratids disappeared, and the fauna was dominated by brachiopods. Brachiopods generally prevailed during Moorehouse and Seneca times, but many local differences are reflected in lithologic and faunal variations.

Toward the east the change from Edgecliff to Nedrow to Moorehouse was gradual. The change was sufficient for the recognition of those units today, but the contacts are gradational and some mixing of faunas is evident. Some of the Edgecliff corals are found in the Nedrow and Moorehouse in their eastern facies, and in the Albany to Catskill quadrangles these corals can not be used to identify the member. In spite of the uniform conditions of the eastern area, the Nedrow platyceratids spread widely and identify the member. Under the uniform conditions the Nedrow fauna persisted longer, and in the area between the Helderbergs and Kingston it characterizes beds that may be equivalent to Moorehouse beds farther west.

The platyceratids, with the exception of *Platyceras dumosum*, were not important during Moorehouse time. In the east, however, corals reminiscent of Edgecliff types lived with the Moorehouse brachiopods in the shallower, cleaner environment of that area.

Toward the southeast, conditions were never as favorable for benthonic life as they were much of the time in the central and eastern areas. The changes which produced the general succession of faunas to the north do not appear

to have affected this area. The Edgecliff is recognized only by the persistent crinoid columnal, and represents an environment similar to that of the Moorehouse. The platyceratids did not live in the area south of Kingston, and the Nedrow member cannot be recognized.

The Moorehouse member is incompletely known in the southeastern area. Locally at least the conditions inhibited normal benthonic life; the undersized fauna at Wawarsing and Port Jervis indicates this. Normal faunas are reported from Pennsylvania, and these may have prevailed much of the time.

Pelagic faunas add to the picture. Cephalopods occur mainly in the central facies of the Moorehouse. This may be a matter of preservation, or the animals may have preferred living over the deeper, less agitated bottoms where scavenging would have been less dangerous. The trilobites were probably semipelagic and are found in most environments. In the southeastern Moorehouse, where normal benthonic fossils are absent the trilobites are the most characteristic fossils.

The Onondaga environments were succeeded by Marcellus black mud conditions. The change was transitional but probably took only a short period of time at any one place. The flood of mud came from the east in late Moorehouse time and reflects early movements of the Acadian Revolution. As the Marcellus environment encroached westward the faunas shifted also. The Tioga benthonite represents a widespread ash fall which apparently hastened the westward shift of the faunas. Although limestone deposition prevailed for a long time after the ash fall in central New York, few of the Moorehouse brachiopods are found. Farther west, however, they persisted in an environment little changed by the eastern events.

At the time of the ash fall, the boundary between the areas of limestone and black shale deposition was just east of Cherry Valley. Farther west the Seneca member represents marginal conditions, but predominantly limestone deposition. The presence of abundant fossils of comparatively few species usually indicates an unfavorable environment. Considerable black mud was introduced, and most of the brachiopods were adversely affected. *Chonetes lineatus* and *Chonostrophia reversa* thrived, however, and are characteristic of these beds. These species are also found in the uppermost transitional Moorehouse farther east, where similar conditions prevailed.

The relationships of the members to theoretical time planes are uncertain. The Tioga bentonite clearly indicates that the Onondaga-Marcellus contact is younger to the west and that the Moorehouse-Seneca contact is a time plane.

The persistence of the large crinoid columnal in the Edgecliff, even in the southeastern facies, suggests that deposition was essentially contemporaneous. The base of the member, however, varies in age from place to place. As the Edgecliff thins to the southeast its base is younger. The member also thins to the west, and it is likely that the basal unconformity in the central and western areas is younger to the west.

The thinning of the Edgecliff in both directions from the Helderbergs may be due to variation in the time of initial deposition, and the Edgecliff-Nedrow contact may be of constant age. This would be so if Edgecliff conditions were terminated suddenly by widespread deposits of mud such as introduced Nedrow times in the central and eastern areas. Such a uniform, thin, stratigraphic unit as the lower Nedrow is not likely to vary much in age.

Age variation of the Nedrow-Moorehouse contact in the Helderberg region and in the southeastern are is indicated in Figures 3 and 4. In the eastern and central areas also, the contact is determined on a faunal basis, and it is doubtful that the platyceratids disappeared everywhere at once.

The Onondaga formation is part of a single depositional phase that becomes younger to the west. Within New York the formation represents continuous deposition, but is divisible into a number of units. The most significant dividing lines are the Edgecliff-Nedrow contact and the Tioga bentonite horizon separating the Moorehouse and Seneca. Both approximate time lines over much of New York and the former may separate lower and upper Onondaga faunas.

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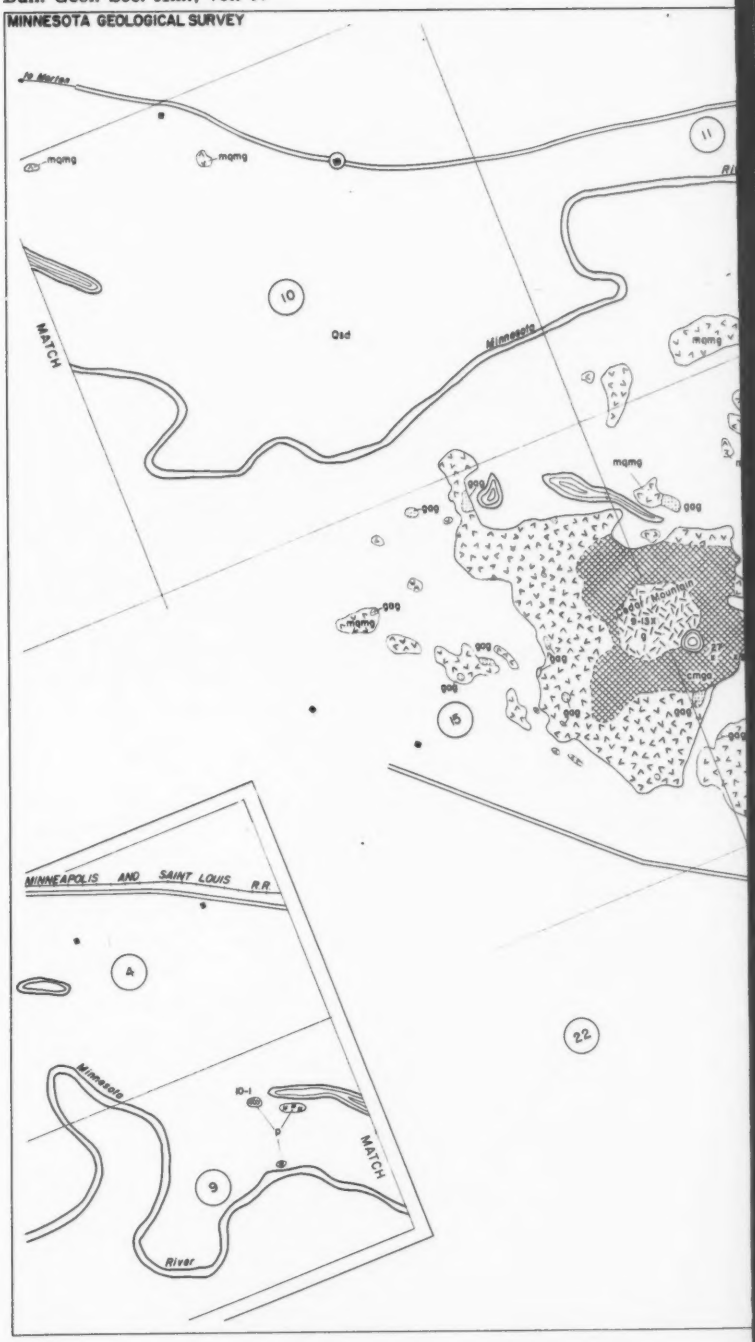
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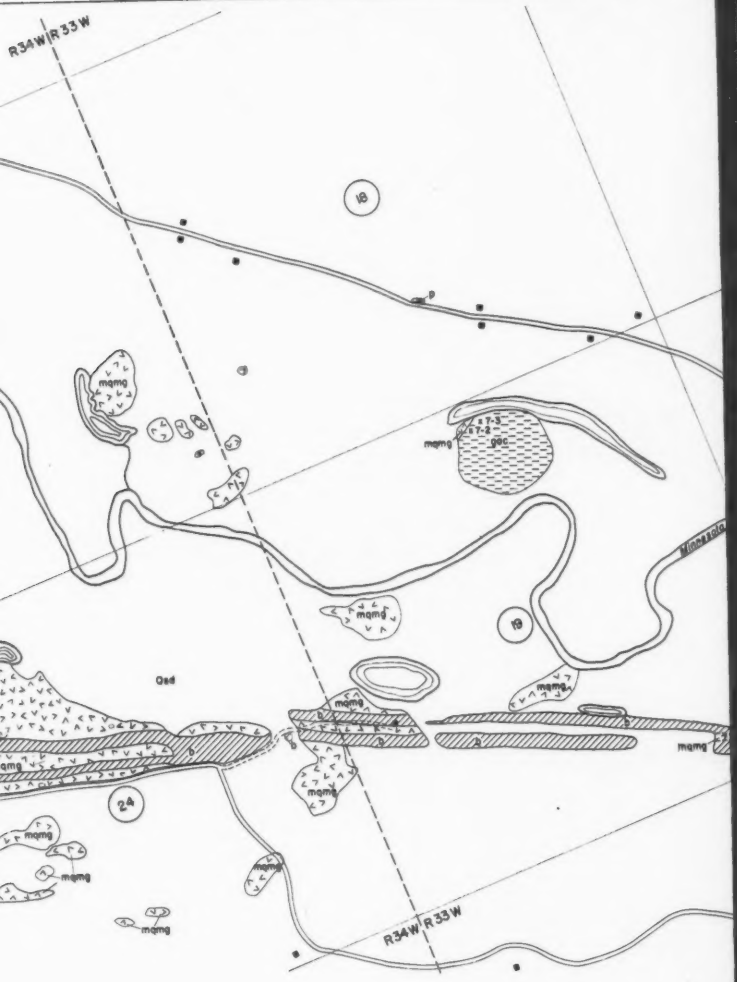

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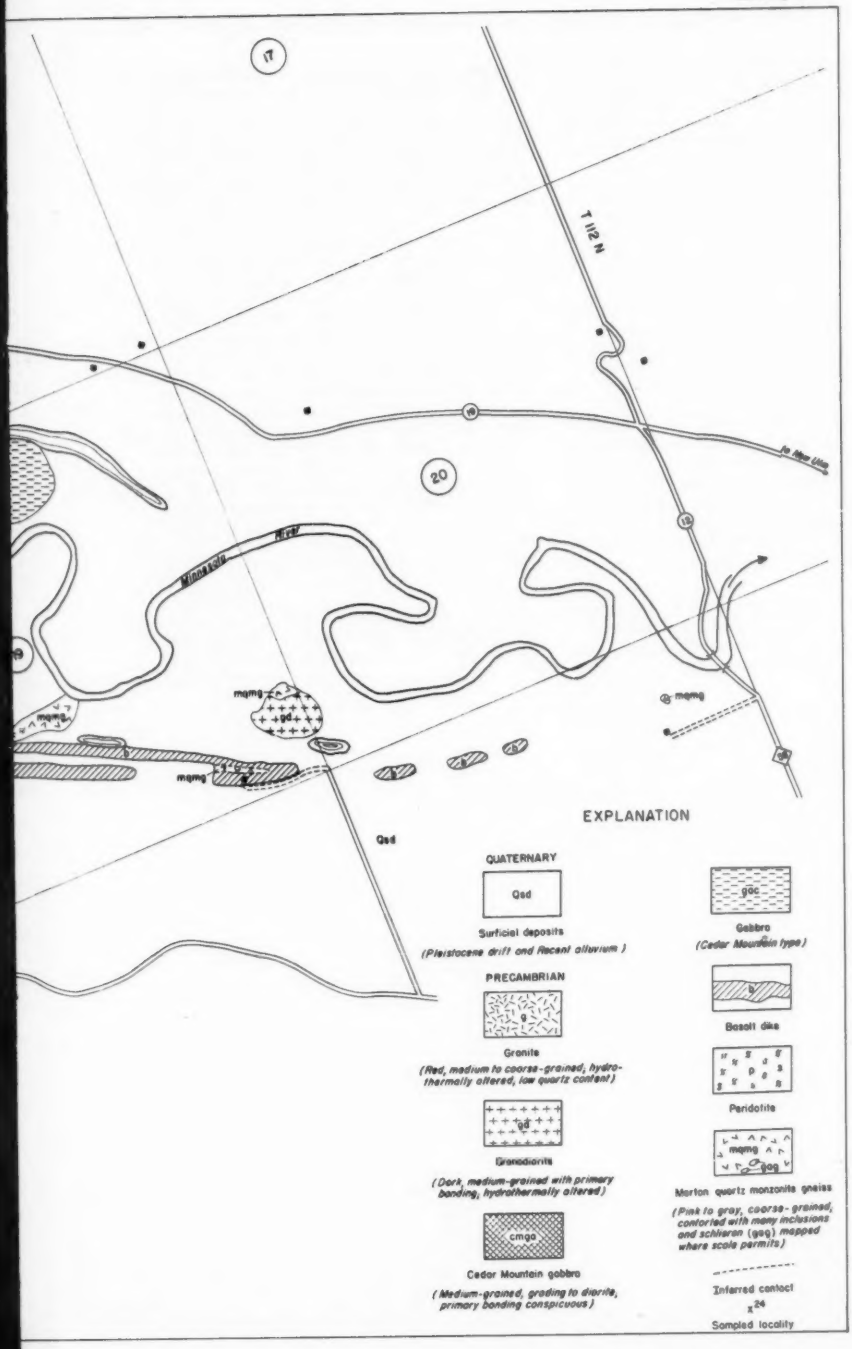
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(Dark, medium-grained with primary banding, hydrothermally altered)
cmgg
Cedar Mountain gabbro
(Medium-grained, grading to diorite, primary banding conspicuous)
gbc
Gabbro
(Cedar Mountain type)
b
Basalt dike
p
Peridotite
mqmg
gneiss
Morton quartz monzonite gneiss
(Pink to gray, coarse-grained, contorted with many inclusions and schlieren (gneiss) mapped where scale permits)
Inferred contact
Sampled locality

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 1475-1490, 1 FIG., 7 PLS. NOVEMBER 1956

IGNEOUS AND METAMORPHIC ROCKS OF THE MINNESOTA RIVER VALLEY

BY ERNEST H. LUND

ABSTRACT

The Precambrian igneous and metamorphic rocks exposed in the Minnesota River Valley between New Ulm and Ortonville are divided into three groups. The oldest is a basic complex of gabbro and diorite gneiss, quartz diorite gneiss, and garnetiferous quartz diorite gneiss. A few small isolated masses of serpentinized peridotite are included in the basic complex. The second group comprises varieties of granite and granite gneiss that are closely related and are assigned to the Minnesota Valley granite series. Five types are distinguished on the basis of textural and structural differences. The third and youngest group, referred to as postgranite intrusives, consists of several small and somewhat circular intrusives, a large number of basic dikes, and two small masses of late granite. Modes of the principal rock types are given.

The relative ages of the three major groups were determined by intrusive relationships, but close dating of the various rocks assigned to each group is not possible. On the basis of zircon types the Minnesota Valley granite series is assigned tentatively to late pre-Huronian or Huronian, and the postgranite intrusives are assigned tentatively to Keewenawan.

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Introduction

Statement of Problem

The object of this investigation was to determine the age relationships of the igneous and metamorphic rocks in the scattered outcrops of the Minnesota River Valley. The valley between New Ulm and Ortonville (Fig. 1) is 120 miles in length and rarely exceeds 2 miles in width and although the outcrops are small and scattered, it soon became apparent that detailed mapping was desirable. The outcrops described are the farthest southwest exposures of the Precambrian Shield except for the Sioux quartzite of southwestern Minnesota and southeastern South Dakota. Approximately 5 summer months, 1947–1949, were spent in the field work, and the outcrops were mapped on aerial photographs with approximate scale of 660 feet to the inch. Geologic maps (Fig. 1) were made from the photographs and from county plats; Plates 1, 2, and 3 were selected as most representative to illustrate the present report. The complete series of geologic maps is in open file in the office of the Minnesota Geological Survey at the University of Minnesota.

Acknowledgments

The field work and drafting of the maps were financed by the Minnesota Geological Survey, and the writer is indebted to Dr. G. M. Schwartz, Director. This paper is abridged from a Ph.D. thesis submitted to the Graduate Faculty of the University of Minnesota; the interest and assistance of the staff members of the Department of Geology and Mineralogy are appreciated.

Geologic Setting

The Minnesota River Valley (Fig. 1) extends from Ortonville on Big Stone Lake at the western edge of Minnesota southeast to Mankato where it makes a right-angled bend to the northeast and joins the Mississippi River Valley near Minneapolis. It is a steep-sided valley cut in a gently rolling prairie upland, ranging in width from about half a mile to a little over 4 miles and in depth from about 100 feet to over 225 feet.

From Ortonville to New Ulm the valley's alluvial plain is broken by numerous knobs and low hills of Precambrian igneous and metamorphic rocks (Pl. 4, fig. 1–3). Below New Ulm Paleozoic sediments are exposed on the valley floor and along the valley walls. Where glaciation has not removed them, Cretaceous sands and clays rest on the Paleozoic and Precambrian rocks. Glacial drift more than 100 feet thick in places overlies the Cretaceous.

Considerable distance separates the Precambrian rocks exposed in the Minnesota River Valley from those cropping out in the central part of the state. Because of this isolation the relationship between Minnesota River Valley rocks and other formations in the state is obscure. The major part of the granites and granite gneisses of the Minnesota River Valley are tentatively dated as late pre-Huronian or Huronian on the basis of their malacon and hyacinth zircon, in accordance with the work of Tyler *et al.* (1940). A number of smaller masses of granite with normal zircon are dated Keweenawan.

The Minnesota River Valley was formed during the Pleistocene when the ancient Lake Agassiz drained to the south. According to Upham (1883) the lower part of the valley follows an old drainage course which developed during late Paleozoic and early Mesozoic and guided interglacial and postglacial drainage. Undoubtedly melting ice supplied large volumes of water to the glacial River Warren, and at times the valley may have been filled from wall to wall. That the river had tremendous competency is shown by the huge boulders it moved, some of which are 20 feet or more across. Potholes up to 10 feet deep and scour channels on the highest knobs indicate the stream's abrasive action.

In most places the outcrops are fresh firm rock, but there are some notable examples of weathered rock in the valley. In the area between Morton and North Redwood many of the outcrops have a thin weathered layer, and along the gorge of the Redwood River above its confluence with the Minnesota River the weathered mantle on granite is about 90 feet thick.

The change in drainage of Lake Agassiz to the north greatly decreased the volume of the Minnesota River, until it was no longer able to transport all the available sediment. The present Minnesota River still deposits alluvium over its flood plain, in certain localities to considerable thickness. A water well near the fairgrounds at Montevideo penetrated 162 feet of alluvium and Cretaceous sediments before reaching granite bedrock. The well at the Roman Catholic church in Morton penetrated 40 feet of alluvium and then passed through 105 feet of Cretaceous clays and sands.

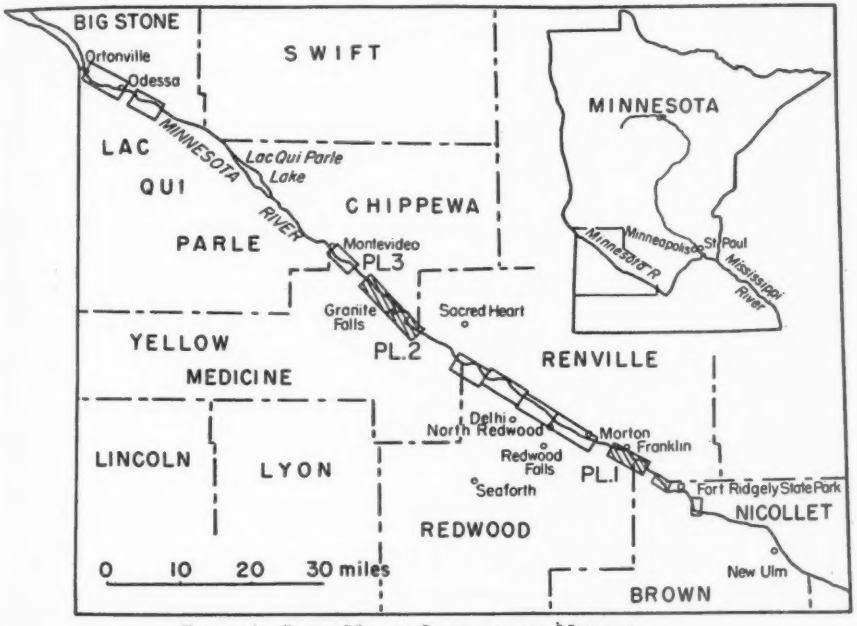

FIGURE 1.—INDEX MAP OF SOUTHWESTERN MINNESOTA

Mapped areas in the Minnesota River Valley and locations of Plates 1, 2, and 3 (shaded). Maps of the unshaded areas are on file at the Minnesota Geological Survey but are not included in this paper.

PETROLOGY

Basic Complex

The basic complex consists of masses ranging from small inclusions in granite to more than a square mile. The rocks are metamorphosed in varying degree, and the wide range in composition depends largely upon the effects of the intruding granites. It is probable that parts of the complex had different origins and initial compositions.

Gabbro and Diorite Gneiss.—Gabbro and diorite gneiss make up most of the basic complex and occur in a large number of dark inclusions and in several larger masses. The principal outcrops are in the vicinity of Granite Falls (Pls. 2, 3), but there are numerable smaller masses between Franklin (Pl. 1) and Montevideo.

Basic inclusions in the granites and granite gneisses range from a few inches across to several hundred feet. Generally they are irregular in shape but in the Granite Falls vicinity they are lenticular with a gneissic structure that is conformable with the structure in the granite gneiss. Some of the irregularly shaped inclusions are distinctly gneissic, and others have no apparent foliation or lineation. Textures range from fine sugary-grained to medium-grained. The smaller inclusions are usually darker and finer-grained.

Because of their superior resistance to disintegration and erosion, the inclusions commonly stand out above the granites and granite gneisses in small rough knobs (Pl. 4, fig. 3). Many of the inclusions have sharp contacts, greater resistance results in their weathering out in positive relief, forming many little crisscrossing ridges. On a slightly weathered surface the ridges give the appearance of welts or seams, "sewed up" rock.

TABLE 1.—MODES OF BASIC GNEISS OF GRANITE FALLS VICINITY
Volume percentage

	Samples from large masses				Samples from small masses					
	1	2	3	4	5	6	7	8	9	10
Plagioclase	75 (An_{71})	72 (An_{65})	45 (An_{53})	60 (An_{44})	43 (An_{54})	43 (An_{55})	37 (An_{43})	43 (An_{51})	45 (An_{43})	22 (An_{45})
Pyroxene	19	14	13	19	25	26	24	X	35	..
Hornblende	6	11	39	7	27	30	38	51	15	76
Accessories:	1	3	5	2	5	1	1	6	1	2
Biotite	..	X	..	X	..	..	X	..	..	..
Magnetite	X*	X	X	X	X*	X	X	X	..	X
Apatite	X	X	X	X	X	X	X	X	X	X
Zircon	X	..	X	..	X	X	X	X	X	..
Quartz	..	X	..	12	..	..	..	..	..	..
Sphene	..	X	..	..	..	X	..	X	..	..

1. Gabbro gneiss (gag), road cut at east edge of Granite Falls. Pl. 3, loc. 69
2. Gabbro gneiss (gag), NW corner Sec. 4, Pl. 2, loc. 34–5
3. Gabbro gneiss (gag), railroad cut, NW corner Sec. 4, Pl. 2, loc. 34-7
4. Silicified diorite gneiss (gag), along railroad siding at rock-crushing plant, Granite Falls. Pl. 3, loc. 36-7
5. Gabbro gneiss (gag), north-central Sec. 14, Pl. 2, loc. 62
6. Gabbro gneiss (gag), NE corner Sec. 33, Pl. 3, loc. 83
7. Diorite gneiss (gag), west edge Sec. 19, Pl. 3, loc. 87
8. Hornblende gabbro gneiss (gag), east edge Sec. 11, Pl. 2, loc. 92
9. Diorite gneiss (gag), railroad cut 1320 feet west and 1020 feet north of SE corner Sec. 20, T. 117 N., R. 40 W.†
10. Hornblende diorite gneiss (gag), east edge Sec. 24, Pl. 2, loc. 30-1

X* usually less than 1 per cent
† Not shown on included maps

and others, especially the smaller ones, grade into the enclosing granite or granite gneiss as a result of partial assimilation. Some were injected with granitic material and have *lit-par-lit* structure.

A characteristic surface feature of inclusions is a crisscrossing of small ridges about an eighth to a quarter of an inch wide (Pl. 4, fig. 4). On some surfaces the ridges are spaced less than an inch apart, and in others the spacing is more than a foot. At some time these rocks were subjected to stresses that produced a complex system of joints. There may be as many as four or five sets of fractures at various angles to each other. Recrystallization of minerals along the joints completely healed them, and their

The largest and most abundant outcrops of gabbro and diorite gneiss are in the Granite Falls area (Pls. 2, 3). In addition to the multitudes of inclusions and a number of larger masses interlayered with the granite gneiss a large area is underlain by gabbro gneiss. The rock of the large mass is generally gray, medium-grained, and gneissic. Near its contact with the granite gneiss it is darker, finer-grained, and more distinctly banded. The rock near the contact is more nearly like that of the inclusions; thus it seems likely that the many inclusions in the granite gneiss were derived from rock similar to that of the large area. Variations in texture, color, and composition are probably dependent largely upon the size

MINNESOTA

GEOLOGIC MAP OF AREA

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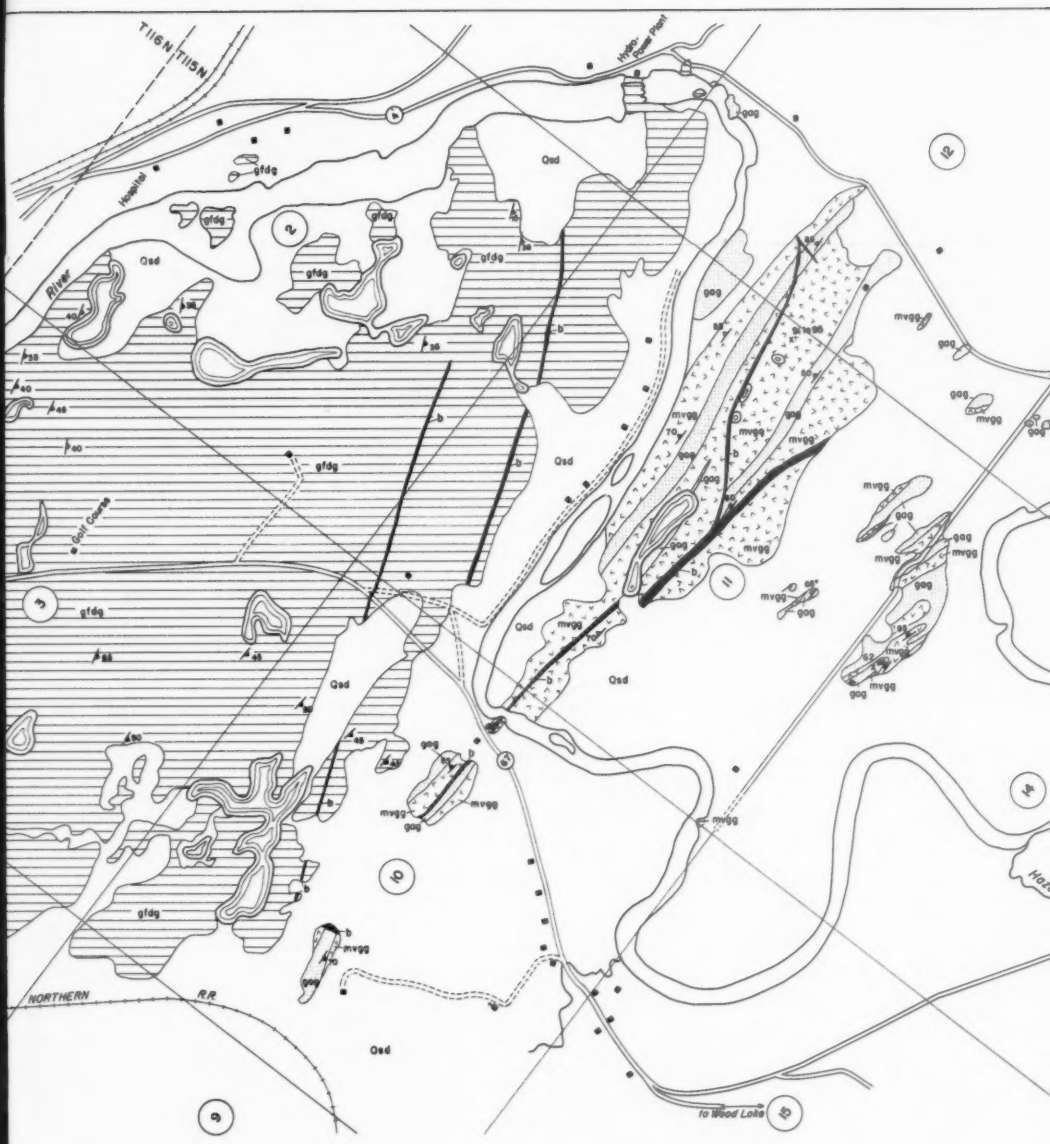
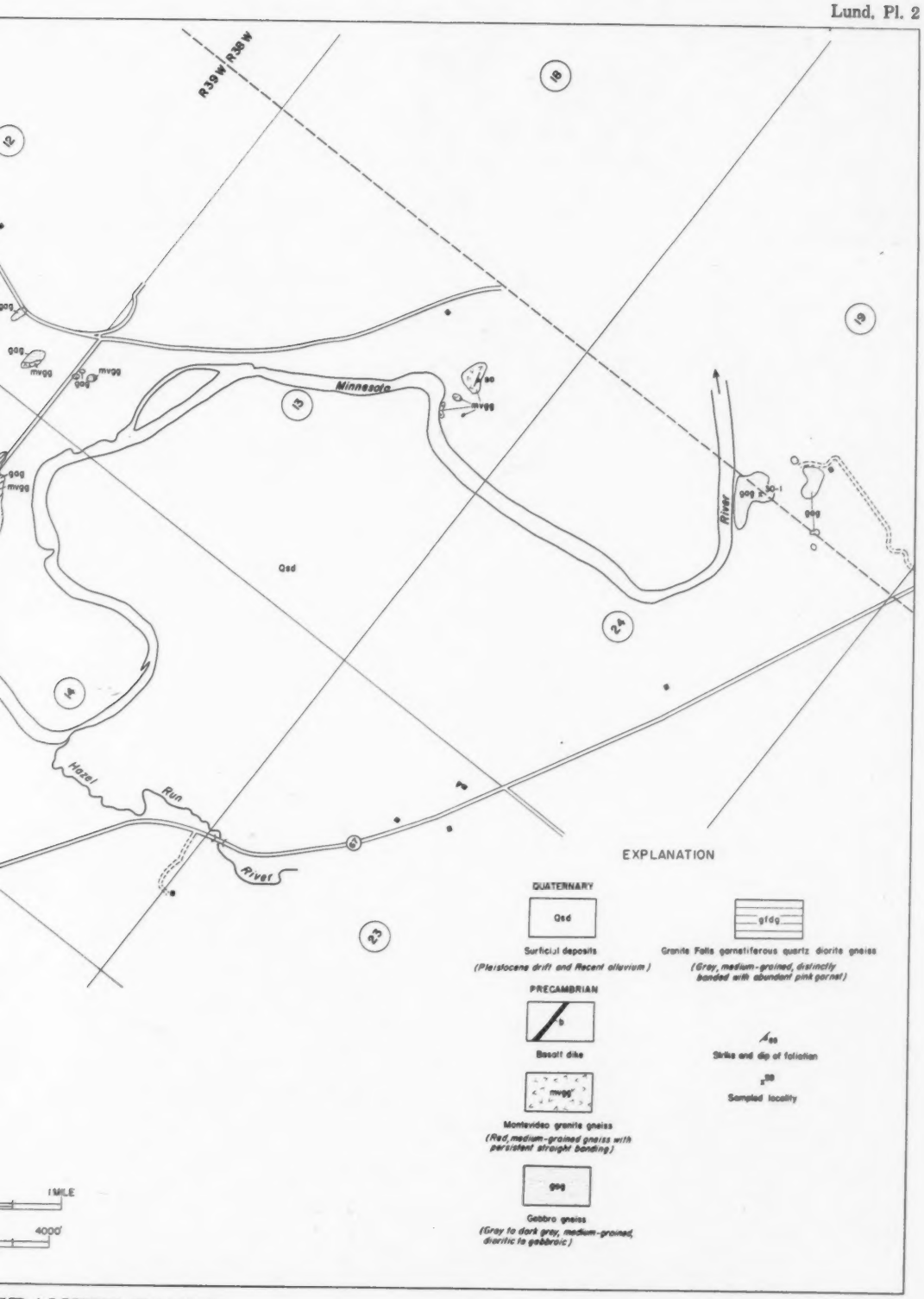


GEOLOGIC MAP OF AREA SOUTHEAST OF GRAND

Chippewa and Yellow Medicine counties, Minnesota
Base map from aerial photographs
Geology by E. H. Lund, 1949



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of the inclusions and the amount of reaction that took place between the inclusions and the invading granite magma.

The large masses of gabbro gneiss in the Granite Falls vicinity and the numerous basic inclusions ranging from diorite to gabbro in the granites and granite gneisses throughout the valley suggest that the basic rock into which the granite magma was introduced was basic igneous rock, probably with some variations in composition and in degree of metamorphism.

Four samples of basic gneiss from the larger masses in the Granite Falls vicinity show some variation in composition (Table 1). The typical gneiss is characterized by high content, 70 per cent or more, of calcic plagioclase (An_{65-71}). Augite is the second abundant mineral, followed by hornblende. Accessory minerals, up to per cent of the rock, include biotite, magnetite, apatite, quartz, sphene, and zircon. Variations are shown in samples 3 and 4. The mode of sample 3 shows 45 per cent plagioclase (An_{48}) and abundant hornblende, 39 per cent of the rock. The sample was collected near the contact of the gabbro gneiss with the granite gneiss, and the composition was modified locally by contact action of the granite. The principal change was recrystallization with the formation of hornblende, in large part at the expense of original calcic plagioclase. There was a definite reduction in the grain size of the gabbro gneiss, and a distinct banding was developed with layers a quarter of an inch wide of hornblende and feldspar alternating with lighter layers of pyroxene and feldspar. The presence of two pyroxenes, augite and hypersthene, distinguishes it from the more typical gabbro gneiss away from the contact with granite. Sample 4 illustrates a second variation of the gabbro gneiss where the rock apparently has been altered with the introduction of quartz. The quartz and andesine (An_{44}) of this rock is the basis for classification as silicified diorite gneiss.

Smaller masses of basic gneiss (Table 1, samples 5–10), of the Granite Falls vicinity are characterized by appreciably smaller amounts of plagioclase and relatively larger amounts of ferromagnesian minerals, notably hornblende. The plagioclase constitutes 36–45 per cent of the rock and ranges from andesine (An_{43}) to labradorite (An_{55}). The inclusions of diorite and gabbro gneiss contain the same accessories as the larger masses. Although these rocks differ from place to place, the differences are mainly in the proportions rather than kinds of minerals. The anorthite content of the plagioclase may differ, and in some places all the pyroxene has been recrystallized to hornblende as a result of contact action.

Inclusions in the Morton gneiss (Pl. 1) and the Sacred Heart granite (not shown on included maps) have differences in composition that bear a close relationship to size. Three samples of large inclusions (Table 2, nos. 11–13) each measuring 30 feet or more across are composed of about 45 per cent calcic andesine (An_{48}) and about 50 per cent pyroxene and hornblende in differing proportions. A fourth sample (Table 2, no. 14) differs from the other three, probably because it is from a larger mass whose occurrence is more similar to those near Granite Falls than to the large inclusions in the Morton gneiss.

In the three samples (Table 2, nos. 11–13) the minerals are fresh and clear, except locally along fractures. The texture is typically sugary-grained and granoblastic. In sample 10 the structure is gneissic with an alignment of hornblende grains. The large amount of hornblende, 39 per cent, probably influenced the development of secondary foliation in contrast to the massive structure of samples 11 and 12, which contain 17–18 per cent hornblende. The latter two samples were collected from inclusions that provide excellent examples of the "sewed-up" structure. Thin sections give a definite clue to the greater resistance which causes differential weathering and formation of the crisscrossing ridges. The ridges are composed principally of hornblende and partially sericitized plagioclase. These minerals were formed by recrystallization that probably was influenced by movement of solutions along the joints. Pyroxene (Goldich, 1938) is less stable than hornblende and will weather at a faster rate. The concentration of hornblende and the absence of pyroxene result in the crisscrossing ridges of the "sewed-up" structure.

Small inclusions (Table 2, nos. 15–18) in the Morton gneiss and Sacred Heart granite are characterized by oligoclase and sodic andesine

(An_{28-34}) and abundant biotite or hornblende, in contrast to the more calcic andesine and abundant pyroxene of the large inclusions. pyroxene. These rocks are classed as amphibolite. Some of the inclusions apparently underwent considerable reaction, with interchange of

TABLE 2.—MODES OF INCLUSIONS IN MORTON GNEISS AND SACRED HEART GRANITE
Volume percentage

	Large inclusions				Small inclusions			
	11	12	13	14	15	16	17	18
Plagioclase	45 (An_{48})	46 (An_{48})	47 (An_{48})	39 (An_{34})	38 (An_{32})	32 (An_{34})	44 (An_{28})	35 (An_{28})
Pyroxene	15	33	33	X	17	....	....	4
Hornblende	39	18	17	58	7	65	53	58
Accessories:	1	3	3	3	3	3	3	3
Magnetite	X*	X	X	X	X	....	X	X
Apatite	X	X	X	X	X	X	X	X
Biotite	X	....	X	....	35	X	....	....
Zircon	X	....	....	....	X	....	X	X
Quartz	....	....	....	....	X	....	....	....
Sphene							X	X

11. Diorite gneiss (gag), at 2570 feet west and 2050 feet south of NE corner Sec. 22, T. 111 N., R. 32 W.†
12. Diorite gneiss (gag) SE ¼ Sec. 14, Pl. 1, loc. 24
13. Diorite gneiss (gag) SE ¼ Sec. 14, Pl. 1, loc. 7–20
14. Hornblende gabbro gneiss (gag), at 500 feet east and 800 feet south of NW corner Sec. 33, T. 114 N., R. 36 W.†
15. Diorite gneiss (gag), quarry 1700 feet west and 2080 feet north of SE corner Sec. 31, T. 113 N., R. 34 W.†
16. Amphibolite (gag), quarry 940 feet east and 1420 feet south of NW corner Sec. 31, T. 113 N., R. 34 W.†
17. Amphibolite (gag), at 440 feet west and 2450 feet north of SE corner Sec. 19, T. 113 N., R. 35 W.†
18. Amphibolite (gag), quarry 2460 feet west and 1010 feet north of SE corner Sec. 18, T. 114 N., R. 37 W.†

X* usually less than 1 per cent
† Not shown on included maps

In the older literature, the basic rocks, both in the larger masses and in the smaller inclusions are classed as gabbro gneiss and schists (Hall, 1899). These rocks are rarely distinct rock types but show many gradations. Fundamentally all the rocks are more or less recrystallized and granoblastic. Commonly recrystallization resulted in reduction of grain size, and the massive sugary-grained rocks, particularly the granular intergrowths of pyroxene and plagioclase, might well be classed as hornfels. In many of the inclusions, especially the smaller ones, considerable hornblende developed at the expense of pyroxene and original calcic plagioclase, resulting in somewhat foliated rocks with abundant hornblende, lesser amounts of oligoclase or andesine, and little or no ions between the solid xenoliths and granite magma. Large amounts of biotite formed in this way. Similarly the hornblende and other minerals may have resulted in part by reactions in accordance with the reaction principle (Bowen, 1928). It follows also that reactions between the solid phase and the granitic magma in large part account for differences in composition of the granite rocks.

Quartz Diorite Gneiss.—The basic inclusions in the Ortonville granite southeast of Odessa are similar in many respects to those in other areas but are characterized by abundant quartz; for this reason they are treated as a separate group. In general it has a fine sugary-grained texture and a structure ranging from massive to schistose with the schistosity im-

parted to the rock by oriented biotite grains. As a rule the alignment of the inclusions conforms to the structure of the Ortonville granite, but in many places within the inclusions there is very complicated folding. Siliceous stringers in the rock are deformed in small tight ptygmatic folds.

TABLE 3.—MODES OF DIORITE GNEISS FROM ODESSA AND GRANITE FALLS
Volume Percentage

	19	20	21
Plagioclase	57 (An_{47})	52 (An_{40})	71 (An_{47})
Pyroxene	15	10	23
Hornblende		X*	X
Biotite	5	X	X
Quartz	21	16	X
Accessories:	2	3	6
Magnetite	X	5	X
Apatite	X	X	X
Garnet	....	14	....

19. Biotite-quartz diorite gneiss (qdg), at 710 feet east and 580 feet south of NW corner Sec. 9, T. 120 N., R. 45 W.†

20. Garnetiferous quartz diorite gneiss (gfdg) NW ¼ Sec. 3, Pl. 2, loc. 72

21. Augite-hypersthene diorite gneiss layer in garnetiferous quartz diorite gneiss (gfdg), roadcut, NW ¼ Sec. 3, Pl. 2, loc. 75

X* usually less than 1 per cent
† Not shown on included maps

A detailed petrographic description of this rock is given by W. S. Bayley (*in* Diller, 1898, p. 358) who classified it as quartz norite gneiss. A number of thin sections from different inclusions were examined, and the mode (table 3, no. 19) was determined from a specimen from one of the larger masses, probably the same outcrop from which Bayley's specimen came. The pyroxene includes both augite and hypersthene, and the latter mineral led to Bayley's classification as norite. The abundant quartz, 21 per cent, is intergrown with the other minerals in a finely granular texture. Because of its sugary texture and nearly massive structure, the rock might be called quartz-bearing pyroxene hornfels. Other smaller masses differ from the measured rock in that the pyroxene has been altered to biotite. Medium plagioclase supports its classification as quartz diorite gneiss.

Granite Falls garnetiferous quartz diorite gneiss.—The Granite Falls garnetiferous quartz diorite gneiss that underlies an area of about 2 square miles south of Granite Falls (Pl. 2) is a distinctive type characterized by abundant pink garnet. It is here named the Granite Falls quartz diorite gneiss. It contains numerous quartz veins and quartz and granite stringers, which in general follow the foliation of the gneiss but frequently cut across it. In some places the large amount of introduced siliceous material results in an abnormally light-gray color. Just south of the Minnesota River in section 3 and extending west in section 4 the garnetiferous quartz diorite gneiss is characterized by a fairly uniform nearly east-west strike of foliation with an average dip of 40 degrees to the south. The structure is reflected in the topography by a number of east-west ridges with scarplike slopes on the north side and more gentle slopes on the south. In general the strike and dip of the foliation in the gneiss is fairly constant over the outcrop area, but locally the rock is crumpled and broken. The structure trend is continued in the gabbro gneiss on the north side of the river.

The garnetiferous quartz diorite gneiss was described in detail by Bayley and classified as garnetiferous gabbro. The texture is medium grained, and the structure is typically banded, although in small outcrops it may appear massive. The rock is variable in composition, and two interlayered phases are represented in Table 3 (nos. 20 and 21). Sample 20 is considered fairly representative. Andesine (An_{40}) makes up over half of the rock. Other minerals are green pyroxene, 10 per cent; quartz, 16 per cent; garnet, 14 per cent; magnetite, 5 per cent; and biotite, hornblende, apatite, and zircon, the remaining 3 per cent. Porphyroblastic garnet is clearly the youngest mineral and contains inclusions of other minerals, chiefly quartz. The nongarnetiferous phase is mainly andesine (An_{47}) with approximately 23 per cent pyroxene, largely augite and minor hypersthene, and accessory minerals which occur in the garnetiferous rock. It is classified as augite-hypersthene diorite gneiss, and its relation to the garnetiferous phase is not clear. In both types plagioclase is fresh with only slight sericitization.

Bent grains, crossed twinning, and wavy extinction are common features, and some of the grains have been granulated with the development of mortar structure.

Lenses of younger granite are locally developed in the garnetiferous quartz diorite gneiss and cut across the quartz and granite stringers mentioned above. This granite is pink, medium-grained, and massive with no evidence of deformation.

Peridotite.—There are three small outcrops of peridotite in the Franklin area in the northeast corner of section 9 (Pl. 1, inset). The rock is highly altered to serpentine with very little of the original olivine and pyroxene remaining. There has been much fracturing, and in places leaching has produced a very porous mass resembling boxwork structure. The void spaces are generally only a fraction of an inch across, but some are several inches. In places the fractures have been filled by bluish and amethystine quartz and a small amount of calcite. Along the road in the southern part of section 18 there is an exposure of weathered rock. Although the original rock is no longer identifiable, the abundance of serpentine suggests that it may have been peridotite.

Minnesota Valley Granite Series

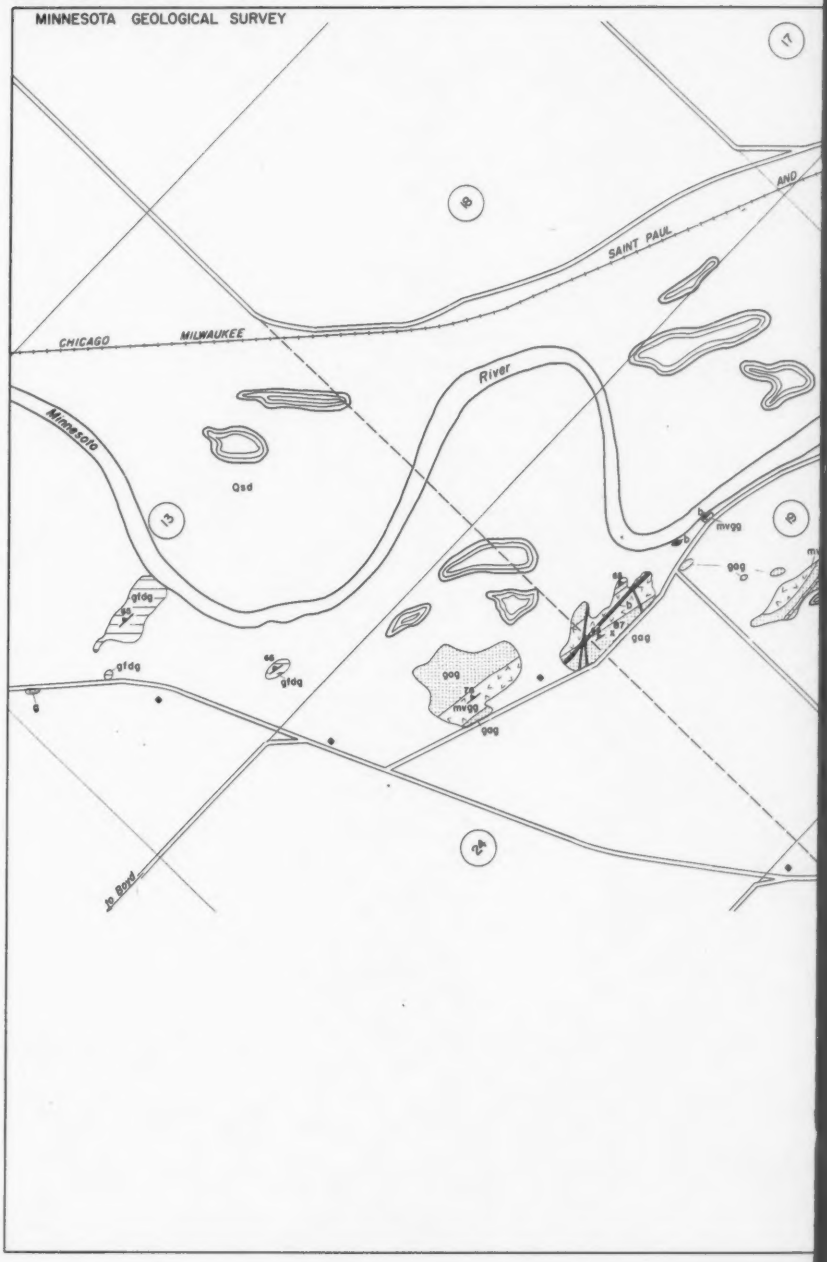
General Statement

Granites and granite gneisses which are younger than the basic complex make up the largest part of the Precambrian rocks of the Minnesota Valley. These rocks were divided into a number of types by G. A. Thiel (1930, unpublished atlas), and a modification of Thiel's divisions is used here. Five rock types are distinguished on the basis of textural and structural characters and are referred to the Minnesota Valley granite series. From the southeast to northwest in the valley these types are: (1) Fort Ridgely granite, (2) Morton quartz monzonite gneiss, (3) Sacred Heart granite, (4) Montevideo granite gneiss, and (5) Ortonville granite. These rocks may not be of the same age, and limited outcrops make it difficult to establish their relations. However, the granite and granite gneiss have many features in common, and there are no apparent chemical and mineralogical differences of importance. The differences in texture, structure, and composition that have been noted can be explained on the basis of local conditions. All the rocks could have been derived from a single magma or closely related magmas during a single period of igneous activity.

Morton Quartz Monzonite Gneiss

The Morton quartz monzonite gneiss, quarried extensively in the vicinity of Morton, is the most widespread of the series and extends approximately 45 miles from a point midway between New Ulm and Franklin to a point south of Sacred Heart (Fig. 1). It is a hybrid rock formed by the strewing out of basic inclusions in a granite magma. It is characterized by a highly contorted structure and displays a great variety of textures and colors. The color is pink to dark gray, depending upon the degree to which the granite magma was contaminated by basic rock. The texture ranges from medium granitoid to very coarse pegmatitic. The pegmatite phase does not consist of distinct veins or dikes but is dikelike in that at many places pegmatitic material cuts across earlier structures. The pegmatite is more in the nature of streaks which disappear by gradation to medium- and coarse-grained gneiss. Aplite dikes, 2–10 feet wide, are numerous in the Morton gneiss and are well exposed in outcrops north of North Redwood.

The complex structure of the Morton gneiss probably resulted from a combination of processes, among which the incorporation of foreign material with the formation of schlieren played a prominent part. A notable effect is the formation of shells of biotite on the inclusions by reaction with the granite magma. By attrition the biotite was scaled off, and the inclusions were reduced to pod-shaped masses (Pl. 5, fig. 1). Some of the smaller inclusions, heated by the magma, were probably in a plastic condition. By plastic yielding and attrition many of them were probably destroyed and assimilated by the magma, appreciably modifying the composition of the magma. The highly contorted structure (Pl. 5, fig. 2) may be in part the result of turbulence in the moving magma, but deformation during cooling when the magma was in large part crystallized probably


MINNESOTA GEOLOGICAL SURVEY
SAINT PAUL
AND
CHICAGO
MILWAUKEE
River
Minnesota
Qsd
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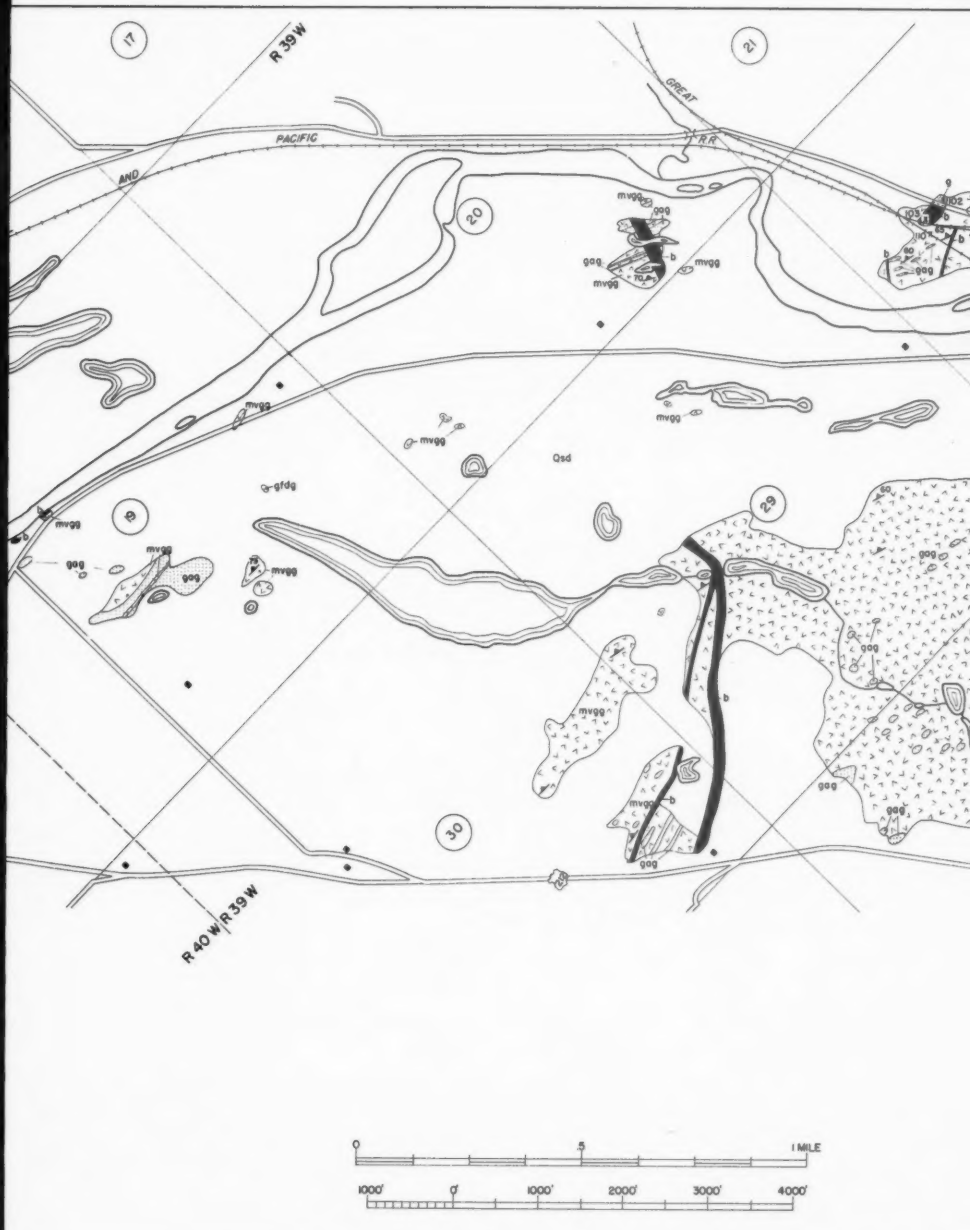

GEOLOGIC MAP OF AREA NORTHWEST OF G

Chippewa and Yellow Medicine counties, Minneso

Base map from aerial photographs

Geology by E. H. Lund, 1949

T OF GRANITE FALLS

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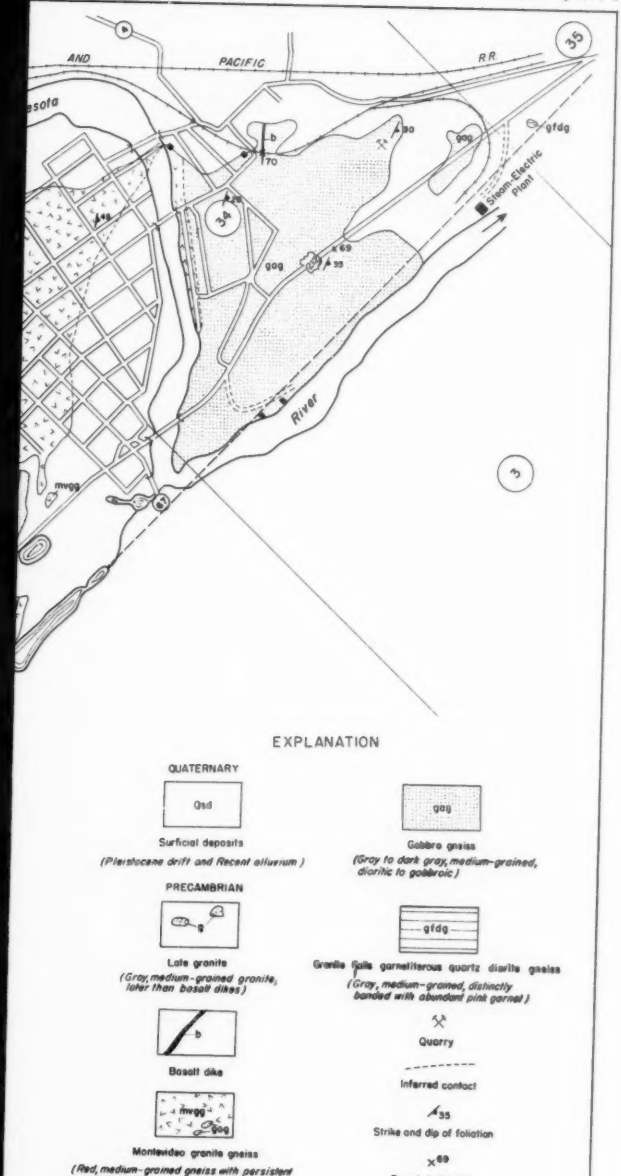
AND
PACIFIC
R.R
35
sota
b
70
80
gog
gfdg
Steam Electric Plant
34
48
28
x 69
35
gog
River
3
mvgg
5
EXPLANATION
QUATERNARY
Qsd
Surficial deposits
(Pleistocene drift and Recent alluvium)
gog
Gabbro gneiss
(Gray to dark gray, medium-grained, dioritic to gabbroic)
PRECAMBRIAN
g
Late granite
(Gray, medium-grained granite, later than basalt dikes)
gfdg
Granite falls garnetiferous quartz diorite gneiss
(Gray, medium-grained, distinctly banded with abundant pink garnet)
b
Basalt dike
Quarry
Inferred contact
35
Strike and dip of foliation
x69
Sampled locality
mvgg
gog
Montevideo granite gneiss
(Red, medium-grained gneiss with persistent straight banding, dioritic to gabbroic inclusions numerous (gog), mapped where scale permits)

was the principal cause. Ptygmatic folds in pink granite stringers which cut the banded structure in gray gneiss indicate that deformation took place while the gneissic rock was still in a plastic condition. Offsets in small late "gash veins" resulted from deformation during he final stages of solidification, and a small amount of granulation with development of mortar structure took place after solidification.

Many of the larger inclusions in the Morton neiss show *lit-par-lit* structure, with closely paced distinct stringers of granite (Pl. 5, fig.). In other inclusions the *lit-par-lit* injection is less distinct, and the action of the magma on the inclusion was more pervasive (Pl. 5, fig. 4). In some of these masses feldspar metacrysts an inch or more long have developed, giving the rock the appearance of augen gneiss.

The inclusions are variable in composition, texture, and structure. The variations are in large part related to the size of the inclusion, which suggests that they are due mainly to reactions between the inclusions and magma rather than to differences in the original rock. The larger inclusions tend to be more basic, nging from dioritic to gabbroic in composi- (Table 2, nos. 11–14). The smaller inclu- are generally more silicic (Table 2, nos. 8). All stages from the relatively unaltered containing pyroxene and basic plagioclase ough the hornblende and medium feldspar rocks to streaks consisting essentially of biotite, silicic plagioclase, and quartz are represented.

In considering its origin, much variation in the composition of the Morton gneiss is expected. Locally where inclusions are numerous and much calcic and ferromagnesian material was incorporated, the resulting gray gneiss is characterized by calcic oligoclase and abundant biotite. The gray gneiss alternates with pink rock which contains potash feldspar. The pink bands are generally coarse-grained, and many are pegmatitic. Modal analyses of 10 samples of Morton gneiss (Table 4) range in composition from leucogranite to quartz diorite. The average of the modal analyses gives quartz 31 per cent, potash feldspar 22 per cent, oligoclase 39 per cent, biotite 6 per cent, and accessory minerals 2 per cent. The average composition from the modal analyses closely approaches an estimate made by Goldich (1938) from chemical and mineral analyses. The chemical analysis is given in Table 5.

Fort Ridgely Granite

The Fort Ridgely granite is a pinkish-gray porphyritic granite with aligned phenocrysts 2 inches or more in length that stand out prominently on slightly weathered surfaces. Dark inclusions are usually small and only locally abundant. Commonly they are strewn out into schlieren that parallel the linear structure defined by the aligned phenocrysts. Foliation within the inclusions does not conform to that of the granite and is variously oriented in different inclusions. This is the result of rotation of the inclusions after they were entrained in the magma. Locally where inclusions are abundant the rock resembles the Morton gneiss, but in general this rock type is more uniform in color, texture, and structure. The typical contorted structure of the Morton gneiss is lacking, and there are few pegmatites. The Fort Ridgely granite is probably a less contaminated and more massive facies of the Morton gneiss. The mode of one specimen (no. 32) is given in Table 6.

Sacred Heart Granite

The Sacred Heart granite in its medium grain, pinkish-gray to red color, and massive to somewhat gneissoid structure is one of the more uniform types of the Minnesota Valley granite series. Inclusions are fairly common but tend to be concentrated in "swarms" rather than being everywhere present as in the Morton gneiss. They are generally a few feet or less across, but there are some that measure more than 100 feet. There was considerable reaction between the inclusions and the granite magma, and various degrees of assimilation are shown, but rarely are the inclusions deformed into schlieren, as in the Morton gneiss.

The Sacred Heart granite and Morton gneiss are found in proximity, but their age relationship is not known. The Sacred Heart granite appears to be younger, but it may represent a younger phase of the magma that produced the Morton gneiss and Fort Ridgely granite.

Four modal analyses of the Sacred Heart

granite (Table 6, nos. 33–36) show the uniformity of this rock. In each case the plagioclase is oligoclase (An_{18}) ranging from 27 to 32 developed in the vicinity of Montevideo and forms extensive outcrops in the Granite Falls vicinity (Pl. 6, fig. 1, 2). It is pink, medium-

TABLE 4.—MODES OF MORTON QUARTZ MONZONITE GNEISS
Volume percentage

	22	23	24	25	26	27	28	29	30	31
Potash feldspar	2	2	2	trace	2	50	51	32	35	44
Plagioclase	57	57	50	60	60	9	14	30	32	25
	(An_{30})	(An_{22})	(An_{26})	(An_{22})	(An_{22})	(An_{18})	(An_{18})	(An_{21})	(An_{22})	(An_{21})
Quartz	24	27	34	32	30	39	34	37	27	26
Biotite	14	11	12	7	5	X	X	X	5	4
Accessories:	3	3	2	1	2	3	1	1	1	1
Magnetite	X*	X	X	X	X	X	X	X	X	X
Apatite	X	X	X	X	X	X	X	X	X	X
Zircon	X	X	X	X	X	X	X	X	X	X
Sphene	X	X	X	X	X	..	..	..	X	..
Epidote	X	X	X	X	X	X	X	..	X	..
Allanite	X	X	X	X	X	..	X	..	..	..
Hornblende	X	X	X	..	X	..	..	..	X	..
Muscovite	..	X	X	..	..	..	..	..	X	..
Johannsen symbol:	228	228	228	228	228	126	126	126″	126″	126″

22. Gray facies of tonalite (mqmg), quarry at Morton 1700 feet west and 2080 feet north of SE corner Sec. 31, T. 113 N., R. 34 W.†

23. Gray facies of tonalite (mqmg), quarry at Morton 1980 feet east and 1450 feet north of SW corner Sec. 20, T. 113 N., R. 35 W.†

24. Gray facies of tonalite (mqmg), at 1510 feet east and 740 feet south of NE corner Sec. 11, T. 113 N., R. 36 W.†

25. Gray facies of tonalite (mqmg), at 890 feet east and 1700 feet south of NW corner Sec. 32, T. 114 N., R. 36 W.†

26. Gray facies of tonalite (mqmg), Cold Spring Quarry, Morton, Minnesota

27. Pink facies of leucogranite (mqmg), Cold Spring Quarry at Morton, Minnesota

28. Pink facies of leucogranite (mqmg), Cold Spring Quarry, Morton, Minnesota

29. Pink facies of quartz monzonite (mqmg), Cold Spring Quarry at Morton, Minnesota

30. Mixed pink and gray quartz monzonite (mqmg), Cold Spring Quarry, Morton, Minnesota

31. Pinkish-gray quartz monzonite (mqmg), at 450 feet east and 200 feet south of NW corner Sec. 22, T. 111 N., R. 32 W.†

X* = usually less than 1 per cent
† not shown on included maps

per cent. Other constituents are potash feldspar 38–44 per cent, quartz 17–26 per cent, biotite and accessories 6–12 per cent. The accessory minerals, including allanite, are all found in the Morton gneiss.

Montevideo Granite Gneiss

Montevideo granite gneiss, which is distinguished from the Morton gneiss primarily by the straightness of its banding, is typically grained, and contains a small amount of dark minerals, except where it is contaminated with the gabbro gneiss which it intrudes. Conspicuous granulation and shearing at numerous places indicate that the structure is largely secondary. Large inclusions of basic gneiss are abundant, particularly in the vicinity of Granite Falls.

The Montevideo gneiss generally is easily recognized but locally where the banding gives way to a crumpled and contorted structure it

resembles the Morton gneiss. Modal analyses (Table 7, nos. 39–42) show that the rock approaches quartz monzonite and in Johannsen's classification averages leucoadamellite. With

TABLE 5.—CHEMICAL ANALYSIS OF MORTON GNEISS FROM COLD SPRING GRANITE COMPANY QUARRY
(S. S. Goldich (1938, p. 22), analyst)

SiO_2	71.54
Al_2O_3	14.62
Fe_2O_3	.69
FeO	1.64
MgO	.77
CaO	2.08
Na_2O	3.84
K_2O	3.92
H_2O^+	.30
H_2O^-	.02
CO_2	.14
TiO_2	.26
P_2O_5	.10
MnO	.04
BaO	.09
S	.02
	100.07

the exception of allanite, the accessory minerals are similar to those in the Sacred Heart granite and Morton gneiss.

Ortonville Granite

The principal outcrops of Ortonville granite lie between Odessa and Ortonville. The same rock type occurs over a large area southeast of Milbank, South Dakota, and there is a small cluster of outcrops a few miles southeast of Odessa. The Ortonville granite is variable in texture, color, and structure. The most common color is red, but in certain localities it is pinkish gray. The texture ranges from medium granitoid to coarse porphyritic with aligned phenocrysts. In many places numerous pink pegmatites give the rock a marbled appearance.

Dark inclusions of quartz diorite gneiss are plentiful in the locality southeast of Odessa, and where they have been partially digested and strewn out the rock has a pronounced gneissoid structure. Where contamination is less marked, the rock has a fairly massive appearance. The porphyritic phase, which is very similar to the Fort Ridgely in appearance, is best developed in this locality. The granite between Odessa and Ortonville is porphyritic in places, but this is not characteristic of the rock in this area. Pegmatite streaks or segregations, which are scarce in the rock southeast of Odessa, are generally prominent in other localities, and in places this material makes up nearly half of the rock.

The variability of the Ortonville granite is marked, and no attempt is made to arrive at an average composition. Two modes of the porphyritic granite from the area southeast of Odessa and two of the red medium-grained granite from the area between Odessa and Ortonville are given in Table 7, nos. 43–46. Microcline is the most abundant mineral in the prophyritic granite and occurs both in phenocrysts and groundmass. Oligoclase (An_{18}) makes up about 15 per cent of the rock. Biotite, approximately 5 per cent, is the essential ferromagnesian mineral. Microcline of the phenocrysts contains inclusions of all the other rock minerals, but the fact that it occurs in the groundmass indicates that its growth was continuous and that the grains are phenocrysts and not metacrysts. Late deformation resulted in bent biotite grains and in granulation of the margins of the phenocrysts. Modes of the red granite differ little from those of the prophyritic phase.

POST-GRANITE INTRUSIVES

Dike Rocks

A large number of dark dikes ranging from less than an inch to tens of feet across cut the granites and gneisses. Most of them are basaltic or diabasic, but a number are lamprophyres. They are typically fine-grained and dense, usually with chilled margins. Dikes are well exposed south of Franklin and in the vicinity of Granite Falls.

South of Franklin (Pl. 1) a prominent ridge over 3 miles long and 500 feet wide is formed by two basalt dikes which intrude the Morton gneiss. The dikes, 100 to 150 feet in width, join in a number of places to form a single dike, but over most of the length of the outcrop they are separated by 100 to 300 feet of gneiss.

Both the basalt dike and the Morton gneiss are weathered, but the granular texture of the gneiss causes it to disintegrate and makes it more susceptible to erosion than is the fine-grained tough basalt. For this reason the basalt forms a ridge, and in many places in the Minnesota River Valley where the rocks have been subject to scour and erosion, the basic rocks stand in higher relief than the surrounding granite or granite gneiss.

The large dike south of Franklin is fine- to medium-grained, approaching a granitoid texture in its central part. A specimen from a road cut in section 23 (Pl. 1, loc. 23) consists of calcic palgioclase and augite with abundant magnetite. There is an appreciable amount of quartz and orthoclase in granophyric intergrowth, and the pyroxene grains show some alteration to hornblende. The rock is hydrothermally altered, and chlorite, sericite, epidote, and other secondary products are abundant.

A number of dikes consist essentially of plagioclase and hornblende without augite. A few of these contain essential biotite. An example is a 30-foot dike in a railroad cut about 100 feet southeast of the Chicago, Milwaukee, St. Paul and Pacific Railroad depot in Granite Falls (locality 70). A sample contains hornblende 60–65 per cent, calcic plagioclase ap-

TABLE 6.—MODES OF GRANITES

Volume percentage

	Fort Ridgely granite	Sacred Heart granite				Younger granites	
	32	33	34	35	36	37	38
Potash feldspar	55	41	44	40	38	30	32
Plagioclase	10 (An_{18})	27 (An_{18})	27 (An_{18})	32 (An_{18})	30 (An_{18})	26 (An_{20})	47 (An_{4})
Quartz	30	26	17	21	25	32	11
Biotite	4	3	9	5	5	11	8
Accessories:	1	3	3	2	2	1	2
Magnetite	X*	X	X	X	X	X	X
Apatite	X	X	X	X	X	X	X
Zircon	X	X	X	X	X	X	X
Sphene	.....	X	X	X	X	.....	.....
Epidote	X	.....	.....	.....	.....	X	X
Allanite	.....	X	X	X	X	.....	.....
Hornblende	.....	.....	.....	.....	.....	.....	.....
Muscovite	.....	X	X	X	X	.....	.....
Johannsen symbol:	126	126″	226″	226″	226″	226″	217″

32. Leucogranite (frg) small quarry 1180 feet west and 820 feet south of NE corner Sec. 2, T. 11 N., R. 33 W.†

33. Pink facies of leucoadamellite (shg) quarry south of Sacred Heart 2420 feet west and 1030 feet south of NE corner Sec. 18, T. 114 N., R. 37 W.†

34. Pink facies of adamellite (shg) roadcut 280′ east and 2750 feet south of NW corner Sec. 17, T. 114 N., R. 37 W.†

35. Gray facies of adamellite (shg) quarry south of Sacred Heart 2420 feet west and 1030 feet south of NE corner Sec. 18, T. 114 N., R. 37 W.†

36. Gray facies of adamellite (shg) quarry south of Sacred Heart 950 feet east and 500 feet south of NW corner Sec. 18, T. 114 N., R. 37 W.†

37. Granite (g) intruding basalt dike at Granite Falls, NW M Sec. 28, Pl. 3, loc. 102

38. Granite (g) of Cedar Mountain intrusive, Sec. 15, Pl. 1, loc. 9–13

X* = usually less than 1 per cent

† not shown on included maps

proximately 30 per cent, and biotite and magnetite 10 per cent. The hornblende grains and aggregates embay and cut across the plagioclase

located in sections 14 and 15, forms a prominent knob called Cedar Mountain. This intrusion is about 2000 feet in diameter. Two

TABLE 7.—MODES OF MONTEVIDEO GRANITE GNEISS AND ORTONVILLE GRANITE
Volume percentage

	Montevideo granite gneiss				Ortonville granite			
	39	40	41	42	43	44	45	46
Potash feldspar	32	39	40	61	61	54	42	48
Plagioclase	30 (An_{18})	26 (An_{18})	24 (An_{18})	9 (An_{18})	16 (An_{18})	15 (An_{18})	22 (An_{18})	17 (An_{18})
Quartz	36	30	31	27	16	25	31	31
Biotite	X*	4	4	2	6	5	4	3
Accessories:	2	1	1	1	1	1	1	1
Magnetite	X	X	X	X	X	X	X	X
Apatite	X	X	X	X	X	X	X	X
Zircon	X	X	X	X	X	X	X	X
Sphene	X	X	....	....	....	....	....	....
Epidote	....	....	....	....	X	X	....	....
Muscovite	X	X	X	....	X	X	X	X
Johannsen symbol:	126″	126″	126″	126	226	226	126	126

39. Leucodamellite (mvgg), east edge Sec. 11, Pl. 2, loc. 95
40. Leucoadamellite (mvgg), NW corner Sec. 33, Pl. 3, loc. 88
41. Leucoadamellite (mvgg), NW M Sec. 28, Pl. 3, loc. 110
42. Leucogranite (mvgg), road cut 1360 feet west and 770 feet north of SE corner Sec. 20, T. 117 N., R. 45 W.†
43. Porphyritic granite (og), quarry 1780 feet east and 1550 feet north of SW corner Sec. 15, T. 120 N., R. 45 W.†
44. Porphyritic granite (og), quarry 1780 feet east and 1550 feet north of SW corner Sec. 16, T. 120 N., R. 45 W.†
45. Red medium granitoid facies ot leucogranite (og), quarry 2720 feet west and 2920 feet south of NE corner of Sec. 26, T. 121 N., R. 46 W.†
46. Red medium granitoid facies of leucogranite (og), quarry south of Odessa, Minnesota 680 feet west and 2400 feet north of SE corner Sec. 32, T. 121 N., R. 45 W.†

X* = usually less than 1 per cent
† Not shown on ineludcd maps

grains, suggesting that original pyroxene and some of the plagioclase may have been recrystallized. The basaltic rock intruded by late granite in the railroad cut northwest of Granite Falls (Pl. 3, loc. 103) is composed of plagioclase, hornblende, and biotite, with a large amount of granophyre.

Cedar Mountain Complex and Related Rocks

In the area south and southeast of Franklin (Pl. 1) several small roughly circular intrusives that may be the same age as the basalt dike, intrude the Morton gneiss. The largest of these

isolated masses in section 19 and a small outcrop in the northwest corner of section 24 appear to be related rock types.

Gabbro-diorite makes up the bulk of the rock in Cedar Mountain and forms an outer shell 500 feet thick surrounding a core of granite, which is considered to be a differentiate. Well-developed banding or primary flow structure is characteristic of the Cedar Mountain gabbro and of the related types in other localities. The pronounced banding results from alternating light and dark layers a quarter of an inch to half an inch wide. In the vertical

walls of gabbro at Cedar Mountain the structure stands vertically (Pl. 7, fig. 2). On the scoured rock surfaces the banding forms swirls, many of which are nearly circular (Pl. 7, fig. 1). The banding appears to be the result of a swirling motion in the magma in an advanced stage of crystallization before final consolidation.

A sample (Pl. 1, loc. 9–18a) of the fine-grained border phase consists of labradorite (An_{53}), pyroxene, olivine, and biotite, with accessories, orthoclase, magnetite, hornblende, and apatite. Small phenocrysts are augite, but both augite and hypersthene occur in the fine-grained groundmass. The olivine is largely altered to magnetite and minor serpentine. The orthoclase is interstitial to the labradorite. Samples taken nearer the center of the mass (Pl. 1, loc. 27) differ appreciably from the border phase. They are composed of andesine (An_{41-46}), augite, biotite, and hornblende, with a large amount of quartz and orthoclase in granophyric intergrowth. Magnetite and apatite are accessories. The rock is characterized by an unusual development of replacement minerals ranging from magmatic to hydrothermal. Hornblende has been developed at the expense of augite, and in many grains there are residual cores of pyroxene. Biotite developed at the expense of hornblende. All the minerals have been severely altered by hydrothermal solutions, and sericite, epidote, zoisite, chlorite, and secondary magnetite are abundant. There is nothing in the thin sections to suggest original olivine or hypersthene. The marked mineralogical change between this rock, which is classified as granophyre diorite, and the border facies of olivine trachybasalt is suggestive of progressive differentiation and a genetic relationship between the gabbroic rim of Cedar Mountain and its granite core.

The mode (Table 6, no. 38) of a somewhat weathered sample of the coarse-grained red rock from the central part of Cedar Mountain shows orthoclase 32 per cent, albite (An_4) 47 per cent, quartz 11 per cent, biotite 8 per cent, and accessory magnetite, epidote, apatite, and zircon 2 per cent. The quartz is largely in a micrographic intergrowth with the orthoclase and in the hand specimens is easily overlooked. Like the coarse-grained granophyre diorite, the granite core has undergone considerable hydrothermal alteration with the production of sericite and chlorite and finely divided hematite, which makes the rock red. The hydrothermal solutions probably were related to the magma which differentiated to produce the Cedar Mountain complex. That the granite is a late differentiate, still fluid while the outer rim of gabbro and diorite were completely solid, is indicated by occasional small dikes of granite that cut across the more basic phases.

Several small masses similar in structure and mineral composition to the Cedar Mountain rocks are believed related to the Cedar Mountain intrusive. An occurrence of gabbro southeast of Franklin (Pl. 1, sec. 19) closely resembles the basic border of Cedar Mountain and grades from fine- to coarse-grained. In both the fin and coarse phases the rock is composed o plagioclase, olivine, and biotite, with minor amounts of magnetite, hornblende, apatite, orthoclase, and a trace of quartz. There are small amounts of secondary minerals including magnetite, serpentine, uralite, chlorite, and sericite. Unlike the coarse diorite of Cedar Mountain, however, the coarse-grained rock is relatively unaltered. Possibly the lack of alter-

PLATE 4.—VIEWS OF THE MINNESOTA RIVER VALLEY

FIGURE 1.—Small granite quarry at Morton (Photo by S. S. Goldich)
FIGURE 2.—Outcrops of Sacred Heart granite with valley wall in background
FIGURE 3.—Prominent knob of basic gneiss inclusion in Morton quartz monzonite gneiss
FIGURE 4.—Close-up view of weathered surface of inclusion showing "sewed up" structure

PLATE 5.—STRUCTURES IN MORTON GNEISS

FIGURE 1.—Pod-shaped inclusions and schlieren
FIGURE 2.—Contorted banding
FIGURE 3.—Granite stringers in basic inclusion
FIGURE 4.—*Lit-par-lit* injection with development of metacrysts

FIGURE 2

FIGURE 4

FIGURE 1

FIGURE 3

VIEWS OF THE MINNESOTA RIVER VALLEY

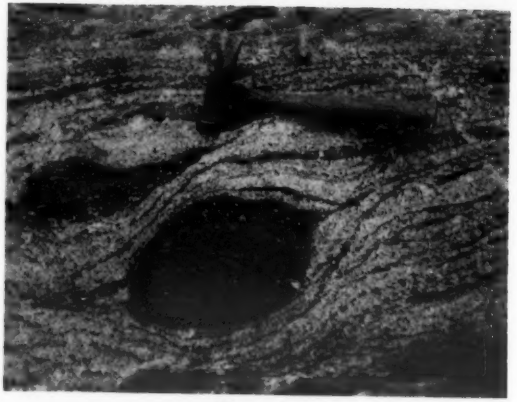

FIGURE 1

FIGURE 2

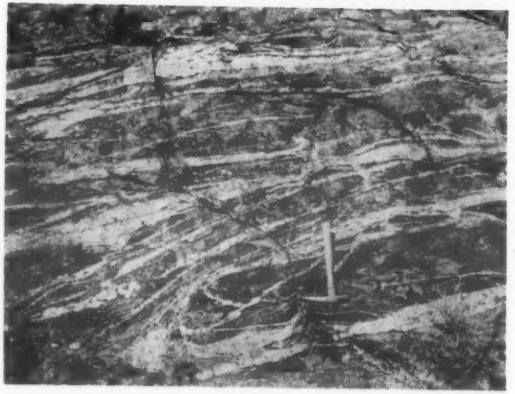

FIGURE 3

FIGURE 4

STRUCTURES IN MORTON GNEISS

FIGURE 1

FIGURE 2

MONTEVIDEO GRANITE GNEISS

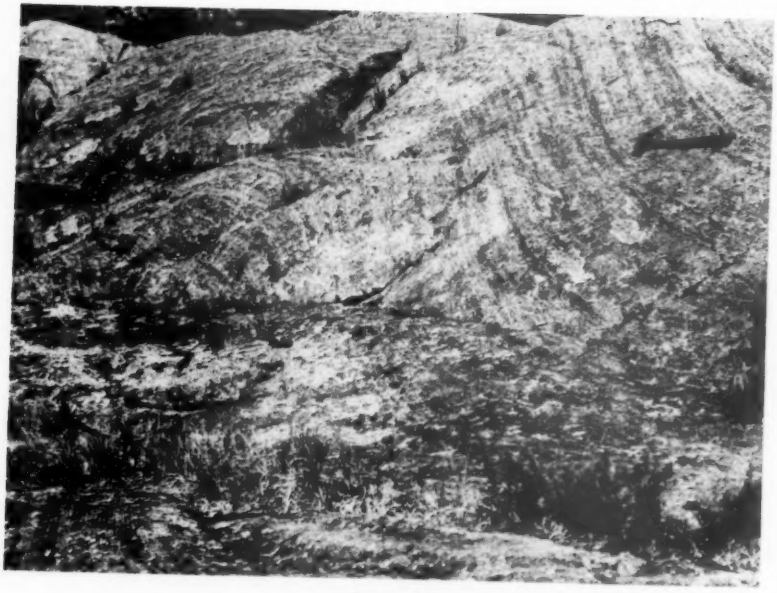

FIGURE 1

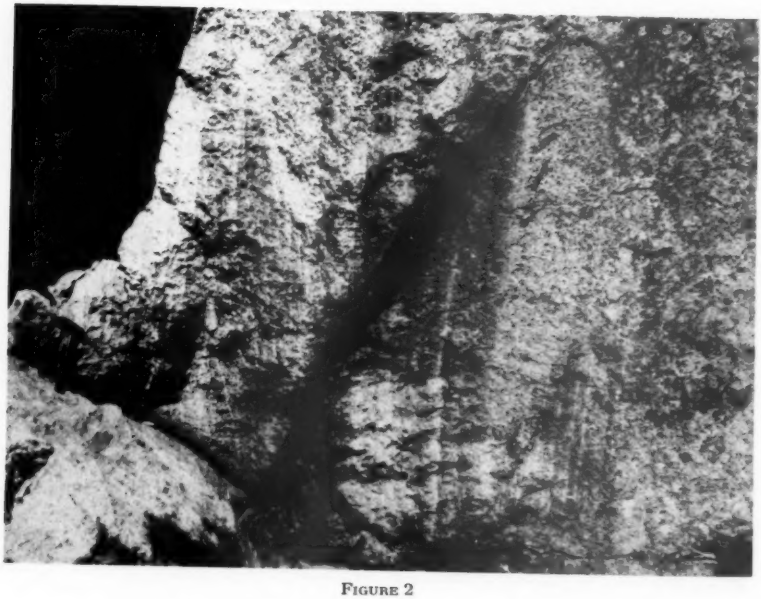

FIGURE 2

BANDING IN CEDAR MOUNTAIN GABBRO

ation can be correlated to the apparent absence of a central granite core.

Two small isolated outcrops of granodiorite southeast of Franklin, one shown in the southeast corner of section 19 and the other not on the map, resemble the Cedar Mountain intrusive in texture and structure. These rocks are nearly 50 per cent hornblende, silicic to medium plagioclase, and quartz and orthoclase in granophyric intergrowth. The hornblende is comparatively fresh, but the plagioclase is much altered to sericite, calcite, and epidote. These rocks are tentatively classed with the granite phase of the Cedar Mountain complex, but their limited extent and lack of contact relations make positive correlation impossible.

Late Granite

An occurrence of late (postbasalt) granite is well exposed in a railroad cut in the NW¼ sec. 28 (Pl. 3). Age relationships are easily determined here. The granite has invaded, cutting a basalt dike that in turn cuts the Montevideo gneiss, which has typical inclusions of gabbro gneiss. A very unusual rock has resulted from the invasion of the late granite magma. The basalt dike was brecciated, and pieces ranging from less than 1 inch up to about a foot are contained in the medium-grained granite, forming an unusual igneous agglomerate. Reaction with the granite magma has tended to round the basic fragments, and from a distance the rock resembles a boulder conglomerate. Where the granite is closely associated with basalt fragments its color is gray, but where the rock is relatively free of basalt fragments it is pinkish gray. The mode (Table 6, no. 37) of a specimen from the less-contaminated portion shows nearly equal amounts of potash feldspar and oligoclase (An_{20}). Quartz is abundant, 32 per cent, and biotite makes up 11 per cent of the rock. Accessory minerals include magnetite, apatite, and zircon. There is a small amount of secondary epidote, zoisite, sericite, pyrite, chlorite, and sphene. The sphene is closely related to the chlorite and appears to have been formed during the alteration of biotite.

A small isolated outcrop of granite intruding basalt is exposed along U. S. Highway 212 northwest of Granite Falls near the western edge of section 13 (not shown on the map). It appears similar to that described above. Another occurrence of granite younger than basalt is found southeast of Granite Falls in section 11, just south of the pond. Small granite stringers cut the basalt here, and the largest, about 4 inches wide, can be traced a few feet in the granite gneiss. These scattered occurrences suggest that late granite intrusions are widespread though small.

Summary of Geologic History

Although the igneous and metamorphic rocks of the Minnesota River Valley are of Precambrain age, there is little positive evidence for close dating. Samples of each of the granites and granite gneisses were crushed and the zircon separated. In the rocks assigned to the Minnesota Valley granite series both hyacinth and malacon zircon were found, which according to Tyler and co-workers (1940, p. 1432, 1533) dates them as Huronian or late pre-Huronian. In the granite of the Cedar Mountain complex and the one intruding basalt northwest of Granite Falls (Pl. 3, sec. 28), the normal zircon was found, indicating Keweenawan age.

The Minnesota Valley granite series intrudes an older complex of basic gneisses which probably is pre-Huronian, though not necessarily all the same age. These gneisses appear to be metamorphosed igneous rocks, and the manner in which granite intruded them along preferred

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Plate 6.—MONTEVIDEO GRANITE GNEISS

Figure 1.—Surface view showing banding and cross jointing
Figure 2.—Cross-sectional view of banding

Plate 7.—BANDING IN CEDAR MOUNTAIN GABBRO

Figure 1.—Eroded surface showing curved banding (Photo by S. S. Goldich)
Figure 2.—Vertical exposure showing straight banding (Photo by S. S. Goldich)

planes suggests the existence of foliation before the intrusion of granite. Following intrusion and complete solidification of the granites there was deformation during which the granites were slightly granulated and prominent secondary structure was developed in the Montevideo gneiss.

Chilled borders on the basaltic dikes and Cedar Mountain type of intrusives suggest they were intruded after the granites had completely cooled. Although crosscutting relations indicate that the dikes were intruded at different times it is believed that they are not widely separated in time. Normal zircon in the granite of Cedar Mountain suggests Keweenawan age for the small intrusives. The dikes are also considered Keweenawan. The intrusion of a small amount of granite into basalt dikes and earlier rocks probably came near the end of Precambrian igneous activity in the Minnesota Valley region.

The coarse grain of the granite series in the Minnesota Valley and the distribution of outcrops suggest that exposures are part of a deep-seated mass. This region was probably one of long continuous erosion, and there is no record, either in outcrops or in well logs, of Paleozoic or Mesozoic rocks, except for sands, silts, and carbonaceous clays which are assigned to the Cretaceous. Before the deposition of the Cretaceous sediments much of the region, particularly in the vicinity of Redwood Falls (Fig. 1), was reduced to a stable topography, and there was a period of deep weathering. Residual kaolinite clay with abundant quartz and relict structures of the original parent Morton gneiss are exposed to a depth of 90 feet (Goldich, 1938, p. 26) in the gorge of the Redwood River.

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The Florida State University, Tallahassee, Florida

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SEDIMENTS OF LAKE PATZCUARO, MICHOACAN, MEXICO

BY G. E. HUTCHINSON, RUTH PATRICK, AND EDWARD S. DEEVEY

ABSTRACT

The recent sedimentary history of Lake Patzcuaro was investigated by pollen analysis in 1944, and a dry climatic phase, probably hundreds or thousands of years ago, seemed to be indicated by maximal abundance of nonarboreal (grass, chenopod, and composite) pollen. The work of Sears on Lake Texcoco, 250 km east, prompted a reinvestigation of the Patzcuaro pollen sequence and a study of the chemistry and the diatom flora of the sediment cores. On the basis of Sears' Index of Humidity (the ratio of *Quercus* + *Alnus* + *Abies* pollen to the total arboreal pollen, which is minimal in the driest intervals when *Pinus* is most abundant), there is clear evidence of a dry phase within the zone of abundant nonarboreal pollen, but the latter now seems to have no direct climatic significance. Instead, since the nonarboreal pollen, particularly its chenopod (+ amaranth?) component, is most abundant during moist phases just preceding and just following the newly defined dry phase, the fluctuations of nonarboreal pollen seem to reflect agricultural practice and, ultimately, demographic history.

The sequence as now interpreted correlates remarkably well with that from the Valley of Mexico, and, using the archaeologic dates that Sears established there, there are: zone D, pre-Archaic (before 1500 B.C.), dry; zone C, early and middle Archaic (1500–500 B.C.), moist; zone B, late Archaic-Teotihuacan (500 B.C.–A.D. 900), climate fluctuating, but with at least one markedly dry episode; zone A, Nahua (A.D. 900–1521), moist. The few archaeologic data and the folklore from the Patzcuaro region tend to confirm this interpretation. There are some differences between the Patzcuaro and the Texcoco pollen sequences, notably in the less well marked character of the last (moist) phase in Patzcuaro.

Of particular interest is the evidence of relatively intense aridity shown in the cores at the inferred late Archaic or Teotihuacan level: a minimum of Sears' Index corresponds to a strong increase in the calcium content of the sediments, and to a zone having only shallow-water benthic and littoral diatoms, above and below which the normal planktonic diatom flora is recorded. The two independent evidences for increased evaporation or reduced rainfall suggest that the dry phase was due to climatic causes and not to culture or volcanism.

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Introduction

This paper grew out of an attempt to develop a simple method of correlation of the chemical composition of lake sediments with changes in lake level. In studying certain basins in Indian Tibet, it was found that the recent deep-water sediments in lakes lacking effluents had a greater content of CaO than comparable sediments in lakes having outlets (Hutchinson, Wollack, and Setlow, 1943). This suggests that if a lake in a semiarid region varied in level, sometimes lacking and sometimes having an outlet, the related deposits would be more calcareous. Moreover, change in lake level might at times increase and at other times decrease the probability of photosynthetic precipitation of lime, so that such an effect might be apparent in a sufficiently astatic lake in a perennially closed basin. It is not uncommon to find low raised beaches covered with littoral calcareous deposits, some of which seem to have been formed suddenly as the lake fell to a critical level. This phenomenom is well shown in Pangur Tso in western Tibet (Hutchinson, 1939).

To obtain more information on such matters, analyses have been made on two cores from Lake Patzcuaro, Michoacan, Mexico, a lake that has had considerable variations in level. In the course of this work, which confirmed the writers' expectation in a most satisfactory manner, it has been necessary to reconsider the results of an earlier study (Deevey, 1944) on the pollen of the Patzcuaro cores in the light of the studies of Sears (1952) in the Valley of Mexico. The rich and varied diatom flora fossilized in the sediments of the lake has added greatly to the interpretation of these cores. The present study is therefore devoted to three initially separate matters. E. S. Deevey did the original field work and made the pollen analyses, which have been reinterpreted with his concurrence by G. E. Hutchinson. Ruth Patrick, who also visited the lake and made some water analyses, identified all the diatoms and drew the relevant conclusions from them. G. E. Hutchinson supervised the chemical work on the sediments and made some of the analyses. All three authors are jointly responsible for the conclusions.

Acknowledgments

We wish to acknowledge with gratitude a grant in aid from the Penrose Bequest, through The Geological Society of America, which made much of the investigation possible. We also wish to thank Mrs. Mary Townsley and Mr. William Cotter for the care and skill they gave to the routine analytical work, and Miss Martha M. Dimock for making the diagrams. We are particularly indebted to Professor Paul B. Sears for making known to us his most recent Mexican results and for opportunities to discuss our investigations with him on many occasions.

Lake Patzcuaro

Lake Patzcuaro lies at about 19° 35′ N. Lat., 101° 35′ W. Long., altitude *ca.* 2035 m, in a basin of interior drainage in Michoacan. Like the rest of the southern part of the Mexican plateau, Michoacan is a volcanic country; immense late-Tertiary and Pleistocene lava flows have covered a belt of Cretaceous and early Tertiary rocks. One consequence of this volcanism, which continues to the present, has been the dismemberment of the basin now only partly drained by the Rio Lerma. The river rises on the western flanks of the lava bed of Ajusco, which forms part of the western rampart of the Valley of Mexico, and flows westward across alternating belts of lava and dominantly lacustrine sediments (Waitz, 1943). Lake Chapala, through which the river flows just before it reaches the break in slope and drops away to the Pacific Ocean, evidently represents the remnant of a much larger Tertiary or Pleistocene lake, but whether this lake extended southward to include the present basin of Lake Patzcuaro is not clear. The distribution of the characin genus *Chirostoma* implies that Patzcuaro (and the Valley of Mexico) formerly belonged to the Lerma drainage (Meek, 1904; Osorio Tafall, 1946).

The lake is C-shaped, and has five principal islands. The area is about 111 sq. km, and the maximum depth is about 15 m, but the extensive limnologic researches, summarized by DeBuen (1941; 1944a; 1944b) and Deevey (1956), have not included the making of a bathymetric map. Suspended volcanic silt

makes the water turbid, the mean monthly transparency ranging from 1.96 m in January to 1.08 m in October, while the Forel-Ule color ranges from 11.3 to 13.1 (DeBuen, 1944b). The pH ranges from 8.6 to 9.0.

The water is chemically rather peculiar, according to analyses by Weir (Deevey, 1956), being essentially a dilute solution of sodium (and potassium) bicarbonate, with moderate amounts of chloride, little sulfate, and an extremely low alkaline-earth content. Analyses made by Ruth Patrick do not show these peculiarities, but Weir's analysis is to a large extent confirmed by his data for Lake Chapala in the same region. The analysis of Villarello (1909), although very rough, agrees in showing more bicarbonate than chloride. Another incomplete analysis, presumably by Espinosa (Ochoterena *et al.*, 1940), agrees with Weir's in showing 19 mg/l of chloride, but the figure for calcium (70 mg/l) is 4 times higher than Patrick's and 20 times higher than Weir's. Obviously the chemistry of Lake Patzcuaro requires further study.

The level of the lake rises and falls with the seasons with a range of about 60 cm, while the minimum (early summer) water level decreased about 80 cm between 1939 and 1943 (DeBuen, 1944b). There are obscure suggestions of a recent rise in level (DeBuen, 1941) and also of a recent fall (Villarello, 1909). In addition to these published records implying fluctuations during colonial times, Pedro Carrasco, who made ethnographic studies on the island of Jaracuaro in 1940, notes that Tarascan folklore abounds in legends having the same implications. There is, for instance, a tradition that hares were once hunted between Jaracuaro and Janicho by the same methods now used there to hunt ducks. Conversely, it is said that one could formerly go by canoe to Huiramangaro, now several kilometers inland. A shoal known as Pastorio has recently emerged east of Jaracuaro and is a major source of tule for basketry; it is claimed by the islanders on the basis of a tradition that their ancestors farmed it. These legends are almost certainly founded on fact, but are unfortunately vague as to date. More definite is the fact, also noted by Mr. Carrasco, that the Beaumont map, probably based on a late sixteenth-century original (*see* Deevey, 1956, for discussion), shows Japupuato as an island. This locality, proved to be the modern place of that name by the persistent legend that the last kings of Michoacan hid their treasure there, is now a mountain rising from the eastern shore of the Ihuatzio basin.

The archaeologic work of Noguera (1931), who found the older sites at higher levels, suggests that deeper water formerly occupied near-by basins in Michoacan (not necessarily the basin of Patzcuaro). The older cultural material, from Curutaran near Zacapu, was said to be Tarascan, essentially like the modern but more primitive. Recently, however, there has been a tendency (Soc. Mex. Antropol., 1948) to restrict the term Tarascan to the relatively recent (post-Classic) cultures known in the Patzcuaro basin proper, while Noguera (1948) equates Curutaran with Zacatenco II–III. Lake levels are known to have been high (Sears, 1952) in the Valley of Mexico during Zacatenco and early Cuicuilco-Ticoman times (early and middle Archaic, *ca.* 1500–500 B.C.). The high level of Nahua time, which permitted Cortes to conquer Tenochtitlan by water, is also established for Patzcuaro by the evidence of the Beaumont map. Thus, while the archaeologic data from Michoacan are scanty, they provide some independent evidence for the view that moist and dry phases were synchronous in Michoacan and in the Valley, and must have been controlled by climate.

Pollen Studies

General Statement

The pollen profiles of cores P-1 and P-3 were published by E. S. Deevey (1944). He interpreted the observed variations in terms of a progressive if somewhat irregular desiccation during the time span under consideration. Two subsequent publications have, however, suggested the necessity of a careful re-examination of the data. Jonathan Sauer (1950) suggested that the high proportion of chenopod or similar pollen in certain levels is a cultural phenomenon, while Sears (1952) in his studies of the Valley of Mexico has apparently provided a more refined method of investigating the paleoclimatology.

Pollen Profiles and Climatology

Sears concluded that the best climatic index available for the study of Mexican lake sediments is obtained by considering the quantities *Quercus*:*Pinus* and *Alnus*:*Pinus* have been computed separately for each level analyzed. *Abies* is too rare in the profiles to be of interest. Any small variation in the Sears Index that corresponds to systematic parallel variation in

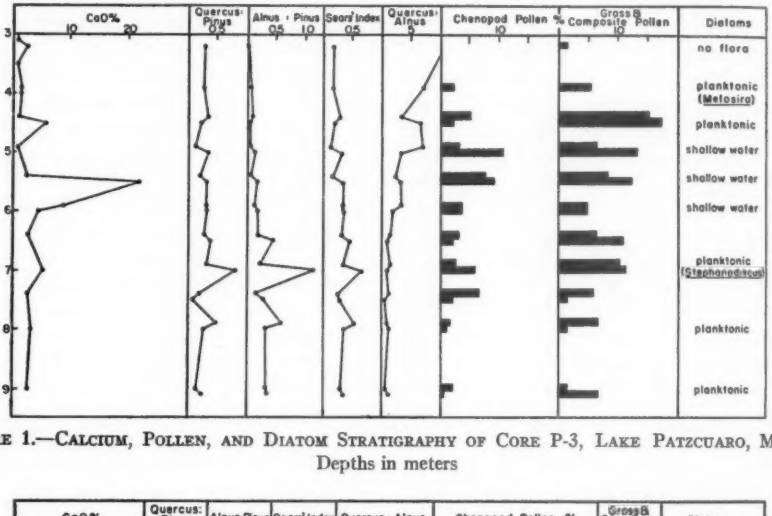

FIGURE 1.—CALCIUM, POLLEN, AND DIATOM STRATIGRAPHY OF CORE P-3, LAKE PATZCUARO, MEXICO
Depths in meters

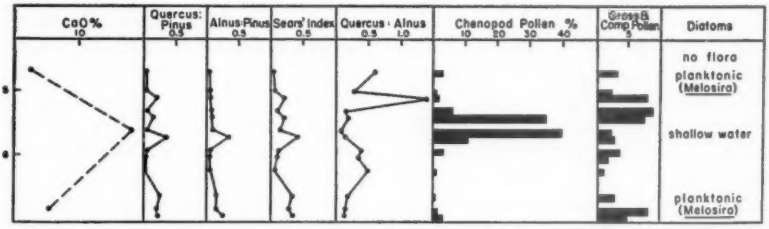

FIGURE 2.—CALCIUM, POLLEN, AND DIATOM STRATIGRAPHY OF CORE P-1, LAKE PATZCUARO, MEXICO
Depths in meters

of oak, alder, and fir relative to pine pollen. In his most recent work (Sears, 1952; Sears and Clisby, 1955) he takes as an index of the climatic regime the ratio of the sum of *Quercus*, *Alnus*, and *Abies* pollen to the sum of the genera *Quercus*, *Alnus*, *Abies*, and *Pinus*, which represents almost the whole arboreal pollen. It is supposed that high values of this ratio, here termed the Sears Index, correspond to wetter periods and low values to drier periods.

In view of the rather small numbers of grains of oak and alder available in the Patzcuaro material and of the complicated variations in the Index recorded by Sears, the ratios both the *Quercus*:*Pinus* and *Alnus*:*Pinus* ratios may be reasonably attributed to a real environmental change, and Sears' climatic interpretation is the most plausible explanation of such a change. When the *Quercus*:*Pinus* and *Alnus*:*Pinus* ratios are compared (Figs. 1, 2), it is apparent that, except near the top where *Alnus* declines to such a low percentage that its variation can have little meaning, there is agreement in the profiles between the minor variations in the two ratios. The use of the Sears Index, therefore, appears to have a strong internal justification.

Considering first the longer core P-3 (Fig. 1), the top meter appears to represent a dry

period; there is a slight but definite wetter phase represented in both the *Quercus*:*Pinus* and *Alnus*:*Pinus* ratios at 4.50 m below the lake surface or 1.5 m below the mud surface. This is preceded by a short but very marked dry episode, prior to which a long period of moderate humidity is recorded. The wettest time of the profile is indicated by three peaks in both ratios: between 6.5 and 7.9 m below the lake surface or 3.5 and 4.9 m below the top of the sediments. The middle maximum is the strongest of the three. The sparse information available relating to the bottom of the core suggests a climate drier than at the time of the succeeding wet maxima, but on the basis of the Sears Index less arid than that of today. Comparison of the top and bottom of the profile is, however, uncertain because above 5 m *Alnus* declines relative to *Quercus*, although the minor variations continue as parallel embroidery. This change may possibly be due to artificial clearing of alder. In view of this possibility it seems likely that the *Quercus*:*Pinus* ratio gives the best evidence of climatic change.

P-1 (Fig. 2) clearly corresponds to that part of P-3 that reaches from the surface of the mud to a little below the first wet maximum at 6.5 m in P-3. There are slight differences in detail, consistent when *Alnus* and *Quercus* are compared within a given core. The most important difference is that in P-1 there seems to have been a marked dry episode around 6 m. The equivalent part of P-3 also lies at 6 m below the lake surface but gives no indication of extreme aridity. The two profiles show clearly less arid conditions from layers now 7 m or more below the lake surface and there are somewhat less impressive though consistent indications of a short wet episode just prior to a modern dry phase. The intervening period exhibits one or perhaps two very dry periods. The original interpretation of the sequence is confirmed, in a general way, as a progression from wet to dry conditions, but it is now apparent that since the time of maximum humidity there have been one or more periods of greater rainfall and one or two periods of greater aridity than at present.

Correlations

The only comparison that can be made is with the work of Sears (1952). Attention must be primarily directed to his profiles 8 and 10, from the Chapingo-Chimalhuacan area along the eastern edge of the bed of Lake Texcoco, which lies east of and once surrounded the site of Mexico City. In these profiles Sears distinguishes four periods.[1]

	Vegetation and climate	*Culture*
A	High oak—moist	Nahua (including Aztec)
B 1	High pine—dry	Early Teotihuacan
B 2	– – ash fall – –	– – – – – – – – – –
B 3	High pine—dry	Late Archaic—Teotihuacan I
C	High oak—moist	Early and middle Archaic
D	High pine—dry	————————

Only the Nahua and the late Archaic are objectively fixed by the discovery of artifacts within the sections. The association of the beginning of the Archaic with the initiation of the earlier wet phase of zone C is purely presumptive though not unreasonable.

Sear's two long profiles (8 and 10) and another profile (9) truncated above the ash zone give evidence of minor climatic fluctuations within the earlier wet zone C, but no consistent pattern is revealed on comparison of the three diagrams, even though they all refer to sediments deposited in Lake Texcoco. One may suspect a complicated pattern of wet maxima set so close together that the sampling interval of 25 cm is not sufficiently narrow to define the variation.

It is reasonable to correlate the irregular wet period, indicated in P-3 by the zone 6.5–7.9 m, with Sears' zone C. The correlation of the three wet maxima with anything exhibited by Sears' profiles is impossible in view of the inconsistency of the latter. It is not unlikely that the bottom of core P-3, from 8.0 to 9.1 m, reaches into Sears' zone D.

[1] The lettering of these zones is of purely local significance, as all Sears' profiles are truncated at the top; Sears' letters have no connection with the letters designating pollen zones in eastern North America (Deevey, 1943) and now widely employed by pollen analysts.

The rise in oak and to a lesser extent in alder in P-3 from a minimum at 4.9 to a secondary maximum at 4.4 m, accompanied by a rise in lake level, as is indicated below, may likewise with fair certainty be correlated with the passage from B to A in Sears' profiles, particularly if oak is a more reliable climatic indicator than alder. This transition is believed by Sears, on archaeologic evidence, to correspond to a rise in the level of Lake Texcoco culminating around A.D. 900, when Teotihuacan gave place to Nahua.[2] It is evident that the wet zone A is far better developed in the pollen diagrams from Lake Texcoco than in those from Lake Patzcuaro. In the Valley of Mexico the later wet phase A is more conspicuous than is the earlier C; in the Patzcuaro basin the reverse is true. This difference requires further investigation.

The fall in lake level recorded in recent years is commonly attributed in Mexico to the development of sinks in the lake floor as the result of volcanic disturbance. Part of the change in the past could perhaps be attributed to such a cause, but the dramatic lowering that culminated at the time of deposition of the sediments 5.5 to 5.9 m below the modern lake surface in P-3 must be put down to enhanced evaporation, as is shown below.

Radiocarbon dating (Arnold and Libby, 1951; cf. Sears, 1952) indicates that the Archaic began at least by 1500 B.C. and persisted for at least a thousand years. If the evidence of a rise in lake level at 4.5 m in P-3 corresponds to the beginning of the Nahua, the top 1.5 m of sediment (3.0 to 4.5 m in P-3) was deposited in a millenium. Extrapolating on the assumption of a uniform mean rate of sedimentation, the beginning of the wet period at 7.9 m would be about 3300 years ago or 1400 B.C., and its end about 2300 years ago or 600 B.C. This is evidently concordant with the radiocarbon dating of the Archaic. On such a chronology, which is tentative, the lowest lake level would have been reached about 1700 years ago, in the third century A.D., and the 6 meters of core P-3 would cover a span of about 4000 years. Comparable rates of sedimentation are indicated in Sears' profiles from Lake Texcoco.

[2] Sears has somewhat oversimplified the culture sequence of the Valley of Mexico; Teotihuacan was first succeeded by Mazapan culture, which centered at Tula, Hidalgo, and was the source of Mexican (Toltec) influence in Yucatan. Nahua, *i.e.*, Aztec culture as understood by archaeologists arose about A.D. 1150. To avoid confusion and a complicated chronologic discussion, Sears' names and dates have been used. Although given in round numbers, these are approximately correct and are probably not affected by changing opinions of Maya chronology (Longyear, 1952).

Nonarboreal Pollen and Agriculture

If an attempt is made to fit the variation in incidence of chenopod and grassland (Gramineae and Compositae) pollen into the scheme defined by the arboreal pollen it is apparent that the nonarboreal pollen has no climatic significance.

In P-3 there is a definite secondary chenopod maximum coincident with the indicators of the wettest period of the profile. This is overlapped by a grassland pollen maximum, the grasses and composites rising and falling slightly later than the chenopods. The whole process is repeated, the chenopods rising to a maximum just before the last wet maximum, and the grasses reaching their greatest numbers at the wet maximum. However, we cannot suppose that, contrary to general expectation, grasses and chenopods are wet indicators in Michoacan, because the greater upper maxima occurred during a less humid period than the earlier secondary maxima. P-1, as far as it goes, tells the same story, although the absolute number of chenopod grains is much larger at the time of the main maximum in P-1 than in P-3. Possibly chenopod pollen is more easily transported to deep water than are other kinds.

Sauer (1950), on the basis of the first report (Deevey, 1944) on the Patzcuaro cores, suggested that the main chenopod maximum represents pollen from a cultivated crop. He suspected that amaranth pollen was confused with that of the Chenopodiaceae and that the crop may have been *Amaranthus leucocarpus*, which is probably of ancient culture in Mexico. The matter has been re-examined, using new preparations made from the sediments by acetolysis, and comparing the grains with those of *Amaranthus leucocarpus* and *A. palmeri*. The decision is difficult, but there is no doubt that the great majority of the fossil

grains are chenopodiaceous. The number of pores is about 52 to 60, with a mode about 56; both amaranths have a modal pore number of 36, although an occasional large (polyploid?) grain of *A. leucocarpus* has 48. Sauer's suggestion may be partly correct, as it is impossible to prove that none of the fossil grains are amaranthaceous. The chenopod (+ amaranth?) pollen maximum almost certainly reflects agriculture, as species of *Chenopodium* are not only well-known agricultural weeds but also have long been cultivated for grain and as vegetables in Mexico, especially in Michoacan.

Whatever the precise nature of the crop may have been, the most reasonable explanation of the observed sequence is that there were two cycles of rather intense cultivation around the lake, an earlier and less extensive cycle during the Archaic, a later and more extensive cycle during a time that appears to correspond to late Teotihuacan in the Valley of Mexico. Late in each cycle it seems likely that an increasing amount of land was abandoned and acquired a transitory covering of grasses and composites, so producing maxima of their pollen just after the chenopod maxima. In view of the occurrence of odd specimens of *Zea mays* pollen at 4.4 and 4.5 m in P-3, at about the time of the last increase in humidity or at the beginning of Sears' zone A, it is conceivable that the second grassland expansion took place when the more efficient maize began to displace less efficient earlier crops. On the tentative chronology outlined above, however, the oldest maize pollen is so young that its occurrence cannot be taken as indicating the time of introduction of maize into the Tarascan country. A probable though admittedly speculative interpretation of the observed variations, if they refer to changes in the extent of agricultural development, is that they reflect demographic changes in the human population around the lake.

The only quasi-historical document of any importance for this area, the sixteenth-century *Relacion de Michoacan* (Anonymous, 1903), presents a picture of political disturbance and warfare between agricultural and rude nomadic tribes in the centuries before the Conquest that is closely (and suspiciously) comparable to the history of the Aztecs before and during their invasion of the Valley of Mexico (Vaillant, 1941). If this picture has any validity it is natural to assign the later abandonment of agricultural land to what would be, roughly, the "Chichimec" period of the historical sources. For the earlier period of interruption of cultivation there is suggestive evidence in the archaeology of the Valley of Mexico, but there seems to be no hope of reconstructing this period by documentary researches.

TABLE 1.—ANALYSES OF CORES P-1 AND P-3
Percentage composition of samples dried at 105°–110° C

Depth, m		Ignition loss	SiO_2	$(Al, Fe)_2O_3$	CaO
P-1	4.70	11.63	40.75	39.09	2.38
	5.60	16.84	40.71	12.51	18.37
	6.80	25.40	48.34	14.33	5.47
P-3	3.0	18.90	40.60	. .	0.59
	3.1	16.90	43.00	. . .	0.92
	3.2	12.45	43.51	39.85	2.49
	3.4	20.00	42.07	. . .	0.33
	3.9	14.91	40.58	35.75	1.51
	4.0	28.70	36.66	. . .	1.50
	4.5	30.07	39.30	17.33	5.72
	4.9	23.90	54.96	. . .	0.93
	5.0	16.33	50.55	24.19	1.22
	5.4	27.40	52.03	. . .	2.64
	5.5	19.00	34.43	12.94	21.63
	5.9	28.40	44.59	. . .	8.70
	6.0	19.38	55.51	13.30	4.55
	6.4	22.90	57.64	. . .	2.76
	6.5	18.60	59.05	. . .	3.90
	6.9	21.50	52.42	. . .	3.04
	7.0	11.93	53.58	22.42	5.30
	7.9	26.20	50.15	. . .	2.15
	8.0	20.80	50.88	19.07	3.10
	9.0	25.60	54.67	. . .	2.97
	9.1	17.85	54.32	18.64	2.72

CHEMICAL DATA

The most striking feature of the chemical analyses (Table 1) is the increase of CaO in the middle of both cores. The period of high calcium deposition of P-3 was limited to a relatively short time when sediments now 5.5 to 6.0 m below the lake surface or 2.5 to 3.0 m below the modern mud surface were being laid down. This period is embraced by the low-

water period indicated by the diatom succession, and occurs at the beginning of one of the driest times recorded by the arboreal pollen.

The deposition of $CaCO_3$ implies a lake level that was falling on account of increased evaporation or decreased precipitation in the catchment basin, and not on account of changes in subaqueous drainage. Local tradition that Lake Patzcuaro feeds the springs above Zacapu in the next valley to the west is unfounded as Villarello (1909) pointed out that the water in these springs is too fresh to have come from the lake. It is important thus to establish that the low water phase in the Patzcuaro basin was due to climatic and not to cultural or volcanic causes, because cultural influence is not ruled out and volcanism is rather favored by the parallel evidence from Lake Texcoco.

There is a suggestion of transitory renewal of calcium precipitation at 4.5 m, but no independent evidence of variations in water level.

The analyses indicate an increase in the sesquioxides relative to silica in the most recent part of the cores. The significance of this is not clear, but it is presumably due to changes in the details of erosion in the drainage basin, changes which may have been largely of cultural origin.

Diatom Studies

General Statement

The diatom studies were made from a portion of the samples taken from certain selected levels of cores P-1 and P-3. The material was cleaned with acid and then thoroughly washed. The diatom material was mounted in a synthetic resin (Hyrax) which has a high refractive index.

In the following section the diatom floras are listed and discussed level by level in each core, whereas Tables 2 and 3 give the occurrences of each species recorded. The slides have been deposited in the diatom collection of the Academy of Natural Sciences of Philadelphia. The number associated with the discussion of each level is the number of the slide in the Academy collection.

Diatoms of Lake Patzcuaro

Core P-1: 4.2 m (A-6836 a, b). No flora.

Core P-1: 4.5 m (A-6838 a, b, c). *Cocconeis placentula*, *Melosira granulata* var. *procera* f. *tenerrima*. Not a true flora; the *Melosira* was of frequent occurrence.

Core P-1: 4.8 m (A-6839 a, b). *Cyclotella* sp., *Diploneis ovalis*, *Epithemia zebra*, *Fragilaria construens*, *F. pinnata*, *Gomphonema parvulum*, *Melosira granulata* var. *procera* f. *tenerrima*, *Rhopalodia* fragments, *Stephanodiscus astraea* var. *minutula*, *S. niagarae*. The only diatom that was at all common was the *Melosira*, a planktonic form often found in warm-water lakes. *Stephanodiscus niagarae*, which is also a planktonic form common in cool, temperate, mesotrophic to eutrophic lakes of North America, was of fairly frequent occurrence. *Fragilaria pinnata*, which has a wide and varied distribution, was also fairly frequent. It is often found in meso- to eutrophic waters. The other species were scarce.

Core P-1: 5.6 m (A-6840 a, b). *Achnanthes exigua*, *Amphora ovalis*, *A. ovalis* var. *affinis*, *Anomoeoneis* sp., *A. polygramma*, *A. sphaerophora*, *A. sphaerophora* var. *sculpta*, *Cocconeis placentula*, *Cyclotella meneghiniana*, *Cymbella cistula*, *C. ventricosa*, *Eunotia lunaris*, *Fragilaria brevistriata*, *F. construens*, *F. construens* var. *venter*, *Gomphonema constrictum*, *G. constrictum* var. *capitatum*, *G. gracile*, *G. gracile* var. *naviculoides*, *G. parvulum*, *Melosira ambigua*, *Navicula cincta*, *N. oblonga*, *N. pupula*, *Neidium iridis*, *Nitzschia amphibia*, *Pinnularia viridis*, *Stauroneis phoenicenteron*, *Surirella tenera*, *S. tenera* var. *nervosa*, *Synedra* sp. This is a typical shallow-water flora, characteristic of a water fairly high in dissolved solids. The lake was eutrophic when this flora was living. The water was probably shallower then than at the time of the 4.8-m or 6.8-m levels. This statement is based on lack of common occurrence of typical planktonic species.

Core P-1: 6.8 m (A-6841 a, b). *Achnanthes exigua*, *A. hungarica*, *Amphora ovalis*, *A. ovalis* var. *affinis*, *Cocconeis placentula*, *Cymbella ventricosa*, *Fragilaria brevistriata*, *F. construens*, *F. construens* var. *venter*, *F. pinnata*, *F. pinnata* var. *lancettula*, *Gomphonema gracile*, *G. gracile* var. *naviculoides*, *G. parvulum*, *G. sagitta*, *Melosira ambigua*, *M. granulata* var. *procera* f. *tenerrima*, *Navicula pelliculosa*, *N. pupula* var. *rectangularis*, *N. pupula* var., *N. radiosa*, *Neidium affine*, *Nitzschia amphibia*, *Rhopalodia gibba*, *Stephanodiscus astraea* var. *minutula*. This flora was composed mainly of species usually found in shallow water. However, the common occurrence of a planktonic species, *Melosira ambigua*, and the frequent occurrence of *M. granulata* var. *procera* f. *tenerrima* indicates fairly warm water, deeper than that found

at the 5.6-m depth. These forms, and the common to frequent occurrence of species of *Fragilaria*, indicate the meso- to eutrophic condition of the water. Lack of *Anomoeoneis* in appreciable numbers may indicate a water lower in dissolved solids.

Core P-3: 3.2 m (A-6842 a, b). No flora; only a few scattered frustules.

Core P-3: 3.5 m (A-6843 a, b). No flora.

Core P-3: 3.9 m (A-6844 a, b, c). *Melosira granulata* var. *procera* f. *tenerrima*. Frustules fairly frequent; no true flora.

Core P-3: 4.5 m (A-6845 a, b, c). *Cocconeis placentula, Cymbella cuspidata, C. ventricosa, Epithemia turgida, Eunotia flexuosa, E. formica, Fragilaria construens, F. pinnata, Melosira ambigua, M. granulata* var. *procera* f. *tenerrima, Navicula exigua* var. *capitata, N. oblonga, N. pupula* var. *capitata, Neidium affine, N. iridis, Pinnularia viridis, Stauroneis phoenicenteron, Stephanodiscus astraea* var. *minutula, S. niagarae*. A definite diatom flora was present, with the planktonic forms *Melosira ambigua* and *M. granulata* var. *procera* f. *tenerrima* commonest. No other species could be classed as common. Several *Fragilaria* species and fragments of *Navicula oblonga* were present. Abundance of *Melosira* indicates fairly deep warm water of meso- to eutrophic condition. The presence of the cool-water form *Stephanodiscus niagarae* and the warmer-water form *Melosira granulata* var. *procera* f. *tenerrima* may indicate that summer and winter floras have been combined by the method of sampling. The presence of species of *Eunotia* and lack of mainly brackish-water species indicate water of low ionic content.

Core P-3: 5.0 m (A-6846 a, b, c). *Achnanthes exigua, Amphora ovalis* var. *affinis, Anomoeoneis polygramma, A. sphaerophora, A. sphaerophora* var. *sculpta, Cocconeis placentula, Cyclotella* sp., *Cymbella aspera, C. cuspidata, C. mexicanum, Epithemia turgida, E. zebra, Eunotia monodon* var. *major, Fragilaria construens, F. construens* var. *venter, Gomphonema acuminatum* var., *G. constrictum* var. *capitatum, Melosira ambigua, M. granulata* var. *procera* f. *tenerrima, Navicula mutica, N. oblonga, N. radiosa, Neidium iridis, Nitzschia amphibia, Pinnularia gentilis, P. viridis, Pinnularia* sp., *Rhopalodia gibba, Stauroneis phoenicenteron, Synedra* sp. This flora is characteristic of shallow water, more alkaline and perhaps more brackish than that at 4.5 m. It consists mainly of epiphytic and benthic species. The commonest were *Epithemia turgida, Cocconeis placentula*, and *Fragilaria construens* and its var. *venter*. The flora indicates eutrophic conditions with a water fairly high in dissolved solids and with a circumneutral to alkaline pH.

Core P-3: 5.5 m (A-6847 a, b). *Achnanthes exigua, Amphora ovalis, A. ovalis* var. *affinis, Anomoeoneis polygramma, A. sphaerophora, A. sphaerophora* var. *sculpta, Cocconeis placentula, Cyclotella* sp., *C. meneghiniana, Cymbella mexicanum, Epithemia turgida, Eunotia monodon* var. *major, Fragilaria construens, F. construens* var. *venter, Melosira ambigua, Navicula oblonga, Neidium affine, N. iridis, N. iridis* var. *amphigomphus, Stauroneis phoenicenteron, Stephanodiscus niagarae*. Fragments of *Navicula oblonga* and specimens of *Anomoeoneis polygramma* were common. These two species are often found in water high in dissolved solids. The same condition is indicated by the frequent occurrence of *Amphora ovalis* var. *affinis* and *Anomoeoneis sphaerophora*. The flora was well diversified but not as rich as that at the 5-m depth. It is characteristically a shallow-water flora in which meso- to eutrophic conditions exist. Sponge spicules were of frequent occurrence.

Core P-3: 6.0 m (A-6848 a, b). *Achnanthes exigua, Amphora ovalis* var. *affinis, Cocconeis placentula, Eunotia flexuosa, Fragilaria brevistriata* var. *inflata, F. construens, F. leptostauron, F. parasitica, F. pinnata, Gomphonema acuminatum* var. *coronata, G. parvulum, Hantzschia amphioxys, Melosira ambigua, M. distans, Navicula bacilliformis, N. confervacea, N. mutica, N. pupula, Nitzschia amphibia, Pinnularia acrosphaeria, Stauroneis phoenicenteron*. The flora, though as diverse as at 5.5 m, was not as abundant in specimens. The only common species was *Fragilaria construens*. This flora is composed mainly of benthic acid and epiphytic species and is therefore characteristic of shallow water. The planktonic species *Melosira ambigua* was a little more frequent than at 5.5 m. This may indicate that the water was somewhat deeper. Sponge spicules were of frequent occurrence.

Core P-3: 7.0 m (A-6849 a, b). *Cocconeis placentula, Epithemia turgida, Fragilaria construens, Melosira granulata, Stephanodiscus astraea* var. *minutula, S. niagarae, S. niagarae* var. *magnifica*. This flora consisted almost entirely of *Stephanodiscus niagarae*, a planktonic form indicating deep, cool water. The shallow-water forms were scarce. The water, from the diatom flora, would appear to have been deeper and cooler than at the higher levels. It was also probably lower in ionic content. The warm-water planktonic species *Melosira granulata* was relatively scarce.

Core P-3: 8.0 m (A-6850 a, b). *Cocconeis placentula, Cyclotella* sp., *Cymbella turgida, Fragilaria construens, F. construens* var. *venter, F. pinnata, Melosira granulata, Navicula oblonga, Neidium iridis, Stauroneis phoenicenteron, Stephanodiscus astraea, S. niagarae, Synedra* sp. The flora was not very rich. The planktonic species *Stephanodiscus niagarae* was common and indicates fairly deep cool water. *Fragilaria construens* and *F. pinnata*

were also fairly common and indicate meso- to eutrophic conditions.

Core P-3: 9.1 m (A-6851 a, b, c). *Achnanthes lanceolata* var. *dubia*, *Cocconeis placentula*, *Epithemia turgida*, *Fragilaria construens* var. *triundulata*, *F. construens* var. *venter*, *F. pinnata*, *Melosira granulata*, *M. granulata* var. *procera* f. *tenerrima*, *Navicula pelliculosa*, *Stephanodiscus astraea* var. *minutula*, *S. niagarae*, *S. niagarae* var. *magnifica*. The diatoms were badly broken but indicate the presence of deep water. There seems to have been a rich flora consisting mainly of *Stephanodiscus niagarae*, *Melosira granulata*, and varieties of *Fragilaria construens*. The common occurrence of both the cool-water species *Stephanodiscus niagarae* and the warm-water form *Melosira granulata* may indicate a mixture of winter and summer floras or a generally warmer water than at 8.0 m. A few shallow-water species were present.

Notes on Ecology and Distribution

These notes have been compiled from the literature and from the unpublished records of the Academy of Natural Sciences of Philadelphia. They represent only what is known at the present about the distribution of these species. All species and varieties identified in the cores but not discussed are listed at the end of this section.

Achnanthes exigua Grunow: Cleve and Grunow. Prefers somewhat alkaline water; indifferent to chlorides of low concentration; can live in warm water; widely distributed in north-central and midwestern states.

Achnanthes hungarica Grunow: Cleve and Grunow. Alkaline water; oligohalobiont, especially in standing waters; cool temperate midwestern and western United States.

Achnanthes lanceolata var. *dubia* Cleve: Cleve and Grunow. Alkaline water; indifferent to low concentrations of chlorides; thermophilous; found in warm, slowly flowing water; tolerant, and may occur in polluted water; widely distributed in temperate North America.

Amphora ovalis Kützing. Alkaline water; oligohalobiont; standing water in detritus of littoral zone; widely distributed in North America, particularly southern and western parts.

Amphora ovalis var. *affinis* (Kützing) Van Heurck. Prefers alkaline water; in United States found in fresh to brackish waters high in carbonates and chlorides.

Anomoeoneis polygramma (Ehrenberg) Cleve. Brackish water; midwestern and southwestern United States.

Anomoeoneis sphaerophora (Kützing) Pfitzer. Fresh to brackish water; halophilous; widely distributed in temperate zone, mainly in western United States.

Anomoeoneis sphaerophora var. *sculpta* (Ehrenberg) Müller. Brackish water; mainly in western United States.

Cocconeis placentula Ehrenberg. Avoids water with low pH; indifferent to low concentrations of chlorides; widely distributed in temperate United States.

Cyclotella meneghiniana Kützing. Prefers alkaline water; halophilous, requiring small amounts of salt to be abundant; usually a littoral form, but sometimes in plankton; seems to be indifferent to H_2S in small amounts; widely distributed in temperate and warm temperate regions.

Cymbella aspera (Ehrenberg) Heribaud. In shallow water; widely distributed in temperate zone, particularly in eastern and midwestern United States.

Cymbella cistula (Hemprich) Kirchner. Prefers somewhat alkaline water; widely distributed in temperate United States.

Cymbella cuspidata Kützing. Seems to be indifferent to low concentrations of salt; widely distributed in eastern and midwestern temperate United States.

Cymbella mexicanum (Ehrenberg) A. Schmidt. Alkaline water; widely distributed in midwestern and western United States and in Mexico.

Cymbella turgida Gregory. Widely distributed in temperate United States.

Cymbella ventricosa Agardh. Indifferent to low concentrations of salt; tolerant of small amounts of H_2S and iron; in shallow water and occasionally in plankton; widely distributed in the temperate zone.

Diploneis ovalis (Hilse) Cleve. Indifferent to low concentrations of salt; widely distributed in temperate United States.

Epithemia turgida (Ehrenberg) Kützing. Prefers water of alkaline reaction; indifferent to small concentrations of salt; prefers shallow areas of standing water; widely distributed in temperate United States.

Epithemia zebra (Ehrenberg) Kützing. Often found in alkaline water; widely distributed in temperate United States.

Eunotia formica Ehrenberg. Most often found in sphagnum or moss bogs in shallow water; may be found in slightly alkaline water; oligohalobiont; temperate to south temperate eastern and midwestern United States.

Eunotia lunaris (Ehrenberg) Grunow: Van

Heurck. pH tolerance wide, but best development is found in acid water rich in humates; widely distributed in temperate United States.

Eunotia monodon var. *major* (W. Smith) Hustedt. Prefers water rich in humates; halophobic; prefers cool temperate regions.

Fragilaria brevistriata Grunow: Van Heurck. Prefers shallow standing water; widely distributed in temperate United States.

Fragilaria construens (Ehrenberg) Grunow. Prefers circumneutral water; indifferent to low concentrations of salt; commonly found in shallow-water zone of lakes; widely distributed in temperate United States.

Fragilaria construens var. *venter* (Ehrenberg) Grunow. Indifferent to low concentrations of salt; widely distributed in temperate United States.

Fragilaria leptostauron (Ehrenberg) Hustedt. Widely distributed in temperate United States.

Fragilaria pinnata Ehrenberg. Prefers eutrophic shallow water; indifferent to small concentrations of salt; more commonly found in temperate and cool temperate areas.

Fragilaria pinnata var. *lancettula* (Schumann) Hustedt. Fresh to slightly brackish water; most often found in western temperate United States.

Gomphonema acuminatum var. *coronata* (Ehrenberg) Rabenhorst. Indifferent to small concentrations of salt; in temperate United States, most often encountered east of the Mississippi River.

Gomphonema constrictum Ehrenberg. Found in cool temperate mountains of Arizona; seems characteristic of higher elevations.

Gomphonema constrictum var. *capitatum* (Ehrenberg) Van Heurck Oligohalobiont; widely distributed in temperate United States.

Gomphonema gracile Ehrenberg. Oligohalobiont; especially well developed in temperate to tropical regions; widely distributed in temperate to warm temperate regions of United States.

Gomphonema gracile var. *naviculoides* (W. Smith) Grunow: Van Heurck. Prefers soft, cool water; widely distributed, particularly in eastern United States.

Gomphonema parvulum Kützing. Tolerant of variable conditions of water; often found in heavily polluted water; widely distributed in temperate United States.

Hantzschia amphioxys (Ehrenberg) Grunow: Cleve and Grunow. Prefers alkaline water; often found in warm water; very tolerant; a cool temperate species, also reported from the Arizona mountains.

Melosira ambigua (Grunow) Müller. A planktonic species that prefers eutrophic water; distributed throughout temperate United States.

Melosira distans (Ehrenberg) Kützing. A planktonic species that prefers cool water; reported only from mountainous portions of cool temperate United States.

Melosira granulata (Ehrenberg) Ralfs: Pritchard. Prefers eutrophic, warm water; often found in cool temperate regions during the summer months.

Melosira granulata var. *procera* f. *tenerrima* (Ehrenberg) Müller. A planktonic form of warm water; in temperate regions; often found only in summer.

Navicula bacilliformis Grunow. Cool temperate and temperate regions, eastern and midwestern United States.

Navicula cincta (Ehrenberg) Ralfs: Pritchard. Alkaline water; grows best in small amounts of salt; widely scattered throughout temperate United States.

Navicula confervacea (Kützing) Grunow. A tolerant species; warm temperate to temperate regions of United States.

Navicula mutica Kützing. Prefers alkaline water with some salt; widely distributed throughout temperate United States.

Navicula oblonga (Kützing) Kützing. Prefers slightly alkaline water; oligohalobiont; widely distributed in temperate United States; most often found in northern part of midwestern and western United States.

Navicula pelliculosa (Brébisson: Grunow) Hilse. A tolerant species; indifferent to low concentrations of salt; not widely distributed; so far, reported in United States only from South Carolina, Tennessee, and Nebraska.

Navicula pupula Kützing. Indifferent to low concentrations of salt; widely distributed in temperate United States.

Navicula pupula var. *rectangularis* (Gregory) Grunow: Cleve and Grunow. Sparsely distributed throughout temperate United States.

Navicula radiosa Kützing. Prefers alkaline water; oligohalobiont; widely distributed in temperate United States.

Neidium affine (Ehrenberg) Cleve. Found in cool temperate United States.

Neidium iridis (Ehrenberg) Cleve. Indifferent to low concentrations of salt; standing water; most often found in cool temperate United States.

Neidium iridis var. *amphigomphus* (Ehrenberg) Mayer. Prefers slightly alkaline water; temperate eastern and midwestern United States.

Nitzschia amphibia Grunow. Prefers alkaline water; oligohalobiont; in shallow areas of lakes;

TABLE 2.—DIATOMS OF CORE P-1, LAKE PATZCUARO, MEXICO

Species	Depth in Meters from Surface				
	4.2	4.5	4.8	5.6	6.8
Achnanthes exigua	..	..	..	2	1
A. hungarica	..	..	..	..	1
Amphora ovalis	..	..	..	3	2
A. ovalis var. *affinis*	..	..	..	3	3
Anomoeoneis sp.	..	..	..	2	..
A. polygramma	..	..	..	3	..
A. sphaerophora	..	..	..	1	..
A. sphaerophora var. *sculpta*	..	..	..	1	..
Cocconeis placentula	..	1	..	3	3
Cyclotella sp.	..	..	1	..	..
C. meneghiniana	..	..	..	2	..
Cymbella cistula	..	..	..	2	..
C. ventricosa	..	..	..	1	1
Diploneis ovalis	..	..	1	..	..
Epithemia zebra	..	..	1	..	..
Eunotia lunaris	..	..	..	1	..
Fragilaria brevistriata	..	..	..	4	3
F. construens	..	..	1	4	3
F. construens var. *venter*	..	..	..	1	3
F. pinnata	..	..	2	..	4
F. pinnata var. *lancettula*	..	..	..	..	4
Gomphonema constrictum	..	..	..	1	..
G. constrictum var. *capitatum*	..	..	..	1	..
G. gracile	..	..	..	1	1
G. gracile var. *naviculoides*	..	..	..	1	1
G. parvulum	..	..	1	1	1
G. sagitta	..	..	..	..	1
Melosira ambigua	..	..	..	2	4
M. granulata var. *procera* f. *tenerrima*	..	3	4	..	3
Navicula cincta	..	..	..	1	..
N. oblonga	..	..	..	2	..
N. pelliculosa	..	..	..	..	3
N. pupula	..	..	..	1	..
N. pupula var.	..	..	..	..	1
N. pupula var. *rectangularis*	..	..	..	..	3
N. radiosa	..	..	..	..	2
Neidium affine	..	..	..	..	2
N. iridis	..	..	..	1	..
Nitzschia amphibia	..	..	..	3	2
Pinnularia viridis	..	..	..	1	..
Rhopalodia fragments	..	..	1	..	..
R. gibba	..	..	..	..	1
Stauroneis phoenicenteron	..	..	..	1	..
Stephanodiscus astraea var. *minutula*	..	..	1	..	1
S. niagarae	..	..	2	..	..
Surirella tenera	..	..	..	1	..
S. tenera var. *nervosa*	..	..	..	1	..
Synedra sp.	..	..	..	1	..

1 = rare. 2 = fairly frequent. 3 = frequent. 4 = common. 5 = abundant.

well distributed throughout temperate United States.

Pinnularia acrosphaeria W. Smith. Slightly alkaline water; oligohalobiont; temperate United States.

Pinnularia gentilis (Donklin) Cleve. Reported only from Pennsylvania in United States.

Pinnularia viridis (Nitzsch) Ehrenberg. Prefers circumneutral water; oligohalobiont; scattered throughout temperate United States.

Rhopalodia gibba (Ehrenberg) Müller. Somewhat alkaline, eutrophic water; often in shallow areas of lakes; indifferent to small amounts of salt; common throughout temperate United States.

Stauroneis phoenicenteron (Nitzsch) Ehrenberg. Prefers shallow water, especially of eutrophic lakes; found throughout temperate United States.

Stephanodiscus astraea (Ehrenberg) Grunow: Cleve and Grunow. A planktonic species of mesotrophic to eutrophic lakes; particularly in temperate and cool temperate United States.

Stephanodiscus astraea var. *minutula* (Kützing) Grunow. Indifferent to low salt concentrations.

Stephanodiscus niagarae Ehrenberg. In mesotrophic to eutrophic lakes; a planktonic species; commonly found in temperate and especially in cool temperate United States.

Stephanodiscus niagarae var. *magnifica* Fricke: A. Schmidt. Recorded only from Mexico as fossil.

Surirella tenera Gregory. A shallow-water species; best development in circumneutral water; oligohalobiont; in temperate United States, but not reported west of Iowa.

Surirella tenera var. *nervosa* A. Schmidt. Seems to prefer warm water; distributed in warm temperate zone, rarely in cool temperate regions (reported in Montana and Iowa).

Species not listed above: *Eunotia flexuosa* (Brébisson) Kützing, *Fragilaria brevistriata* var. *inflata* (Pantoseck) Hustedt, *Fragilaria construens* var. *triundulata* (Ehrenberg) Hustedt, *Fragilaria parasitica* (W. Smith) Grunow, *Gomphonema sagitta* Schumann, *Navicula exigua* var. *capitata* Patrick, *Navicula pupula* var. *capitata* Hustedt: Pascher.

Discussion

An examination of Tables 2 and 3 together with the discussion of the various levels in the cores indicates that there was a general trend from cool deep water to warm shallow water of high ionic content. The water again became deeper, but not as cool as in the early history of the cores.

Most of the species are widely distributed in the temperate zone or seem to have a preference for warm temperate regions. No cold-water or tropical species were found.

Both cores indicate the same general trend in water conditions. Deep cool water support-

TABLE 3.—DIATOMS OF CORE P-3, LAKE PATZCUARO, MEXICO

Species	Depth in Meters from Surface									
	3.2	3.5	3.9	4.5	5.0	5.5	6.0	7.0	8.0	9.1
Achanthes exigua	...	...	...	...	1	1	3	...	...	...
A. lanceolata var. *dubia*	...	...	...	...	...	...	...	...	...	1
Amphora ovalis	...	...	...	...	...	2	...	...	...	...
A. ovalis var. *affinis*	...	...	...	...	2	3	1	...	...	...
Anomoeoneis polygramma	...	...	...	...	2	4	...	...	...	...
A. sphaerophora	...	...	...	...	1	3	...	...	...	...
A. sphaerophora var. *sculpta*	...	...	...	...	1	2	...	...	...	...
Cocconeis placentula	...	...	...	3	4	3	3	2	2	3
Cyclotella sp.	...	...	...	...	3	2	...	...	1	...
C. meneghiniana	...	...	...	...	...	1	...	...	...	...
Cymbella aspera	...	...	...	...	1	...	...	...	...	...
C. cuspidata	...	...	...	1	1	...	...	...	...	...
C. mexicanum	...	...	...	...	1	1	...	...	...	...
C. turgida	...	...	...	...	...	...	...	...	1	...
C. ventricosa	...	...	...	1	...	...	...	...	...	...
Epithemia turgida	...	...	...	3	4	3	...	1	...	1
E. zebra	...	...	...	...	2	...	...	...	...	...
Eunotia flexuosa	...	...	...	1	...	...	1	...	...	...
E. formica	...	...	...	1	...	...	...	...	...	...
E. monodon var. *major*	...	...	...	...	1	1	...	...	...	...
Fragilaria brevistriata var. *inflata*	...	...	...	...	...	...	3	...	...	...
F. construens	...	...	...	2	4	3	4	1	3	...
F. construens var. *triundulata*	...	...	...	...	...	...	...	...	...	1
F. construens var. *venter*	...	...	...	...	4	3	...	...	2	3
F. leptostauron	...	...	...	...	...	...	1	...	...	...
F. parasitica	...	...	...	...	...	...	1	...	...	...
F. pinnata	...	...	...	2	...	...	3	...	3	2
Gomphonema acuminatum var.	...	...	...	...	1	...	...	...	...	...
G. acuminatum var. *coronata*	...	...	...	...	...	...	1	...	...	...
G. constrictum var. *capitatum*	...	...	...	...	1	...	...	...	...	...
G. parvulum	...	...	...	...	...	...	3	...	...	...
Hantzschia amphioxys	...	...	...	...	...	...	2	...	...	...
Melosira ambigua	...	...	...	5	1	2	3	...	...	...
M. distans	...	...	...	...	...	...	2	...	...	...
M. granulata	...	...	...	...	...	...	...	2	2	4
M. granulata var. *procera* f. *tenerrima*	...	...	2	4	3	...	...	...	...	2
Navicula bacilliformis	...	...	...	...	...	...	1	...	...	...
N. confervacea	...	...	...	...	...	...	1	...	...	...
N. exigua var. *capitata*	...	...	...	1	...	...	...	...	...	...
N. mutica	...	...	...	...	1	...	1	...	...	...
N. oblonga	...	...	...	3	3	4	...	...	1	...
N. pelliculosa	...	...	...	...	...	...	...	...	...	1
N. pupula	...	...	...	...	...	...	2	...	...	...
N. pupula var. *capitata*	...	...	...	1	...	...	...	...	...	...
N. radiosa	...	...	...	...	1	...	...	...	...	...
Neidium affine	...	...	...	2	...	2	...	...	...	...
N. iridis	...	...	...	1	2	2	...	...	2	...
N. iridis var. *amphigomphus*	...	...	...	...	...	2	...	...	...	...
Nitzschia amphibia	...	...	...	...	2	...	2	...	...	...
Pinnularia sp.	...	...	...	...	1	...	...	...	...	...
P. acrosphaeria	...	...	...	...	...	...	1	...	...	...
P. gentilis	...	...	...	...	1	...	...	...	...	...
P. viridis	...	...	...	1	1	...	...	...	...	...
Rhopalodia gibba	...	...	...	...	2	...	...	...	...	...
Stauroneis phoenicenteron	...	...	...	1	1	4	1	...	1	...
Stephanodiscus astraea	...	...	...	...	...	...	...	...	2	...
S. astraea var. *minutula*	...	...	...	1	...	...	...	3	...	1
S. niagarae	...	...	...	1	...	1	...	4	4	4
S. niagarae var. *magnifica*	...	...	...	...	...	...	...	4	...	1
Synedra sp.	...	...	...	...	1	...	...	...	1	...

1 = rare. 2 = fairly frequent. 3 = frequent. 4 = common. 5 = abundant.

ing a planktonic flora was present from 9 m through 7 m in Core P-3. *Stephanodiscus niagarae*, a cool-water species, was common in these deeper levels.

The level at 6.8 m in Core P-1 may represent a shallow-water area of a deep lake. A predominantly shallow-water flora with some planktonic forms was found.

The floras at 5.6 m in Core P-1 and at 6.0 and 5.5 m in Core P-3 indicate shallow water with an ionic concentration higher than existed before or after this period. This would be expected if the lake were shallower at this time. This theory is supported by both the kinds of species and the apparent environmental preference of the species.

In the levels at 4.8 m in Core P-1 and 4.5 m in Core P-3 deeper water is again indicated, with the planktonic species of *Melosira* common. In the levels at 3.9 and 3.2 m of Core P-3 and at 4.5 and 4.2 m in Core P-1 no true floras were present.

There is no indication that acid bog conditions ever existed, as is sometimes found in lake development (Patrick, 1954). The diatom species are all characteristic of water of temperate-zone lakes between pH 6 and 9.

The salient features of the diatom stratigraphy have been combined with the pollen and chemical data in Figures 1 and 2.

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Osborn Zoological Laboratory, Yale University, New Haven, Connecticut; Academy of Natural Sciences, Philadelphia, Pennsylvania; Osborn Zoological Laboratory, Yale University, New Haven, Connecticut

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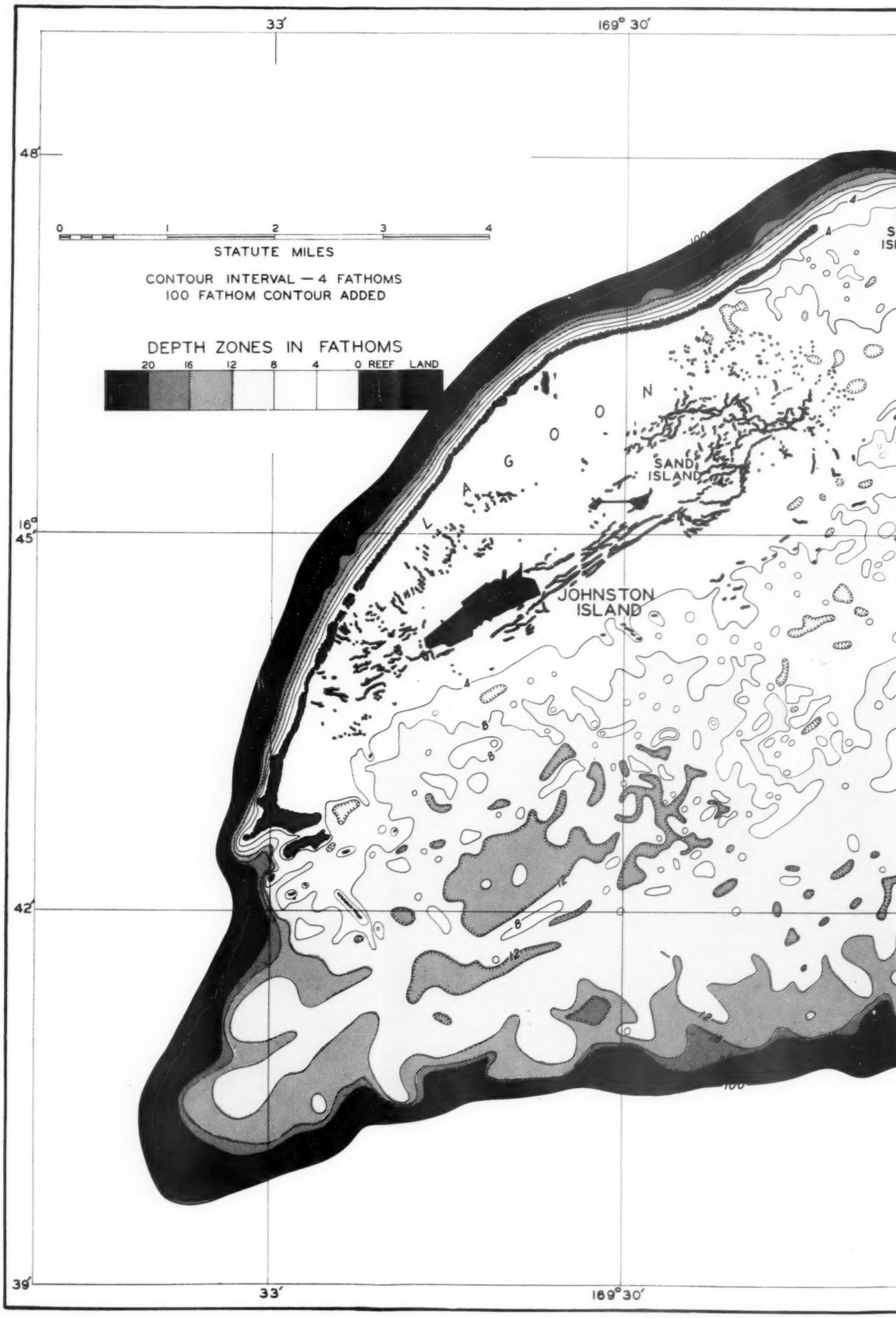

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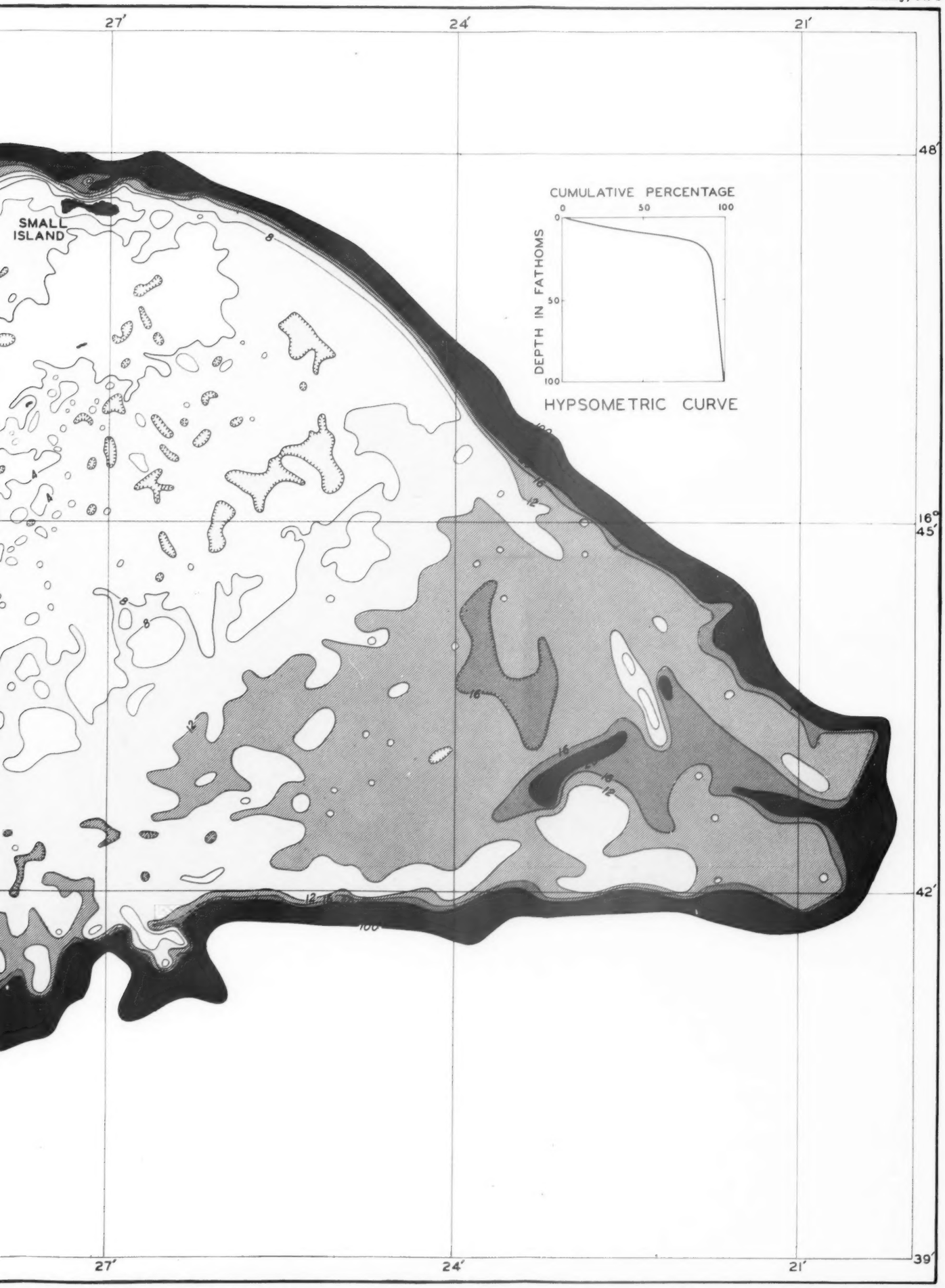

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MARINE GEOLOGY OF JOHNSTON ISLAND AND ITS SURROUNDING SHALLOWS, CENTRAL PACIFIC OCEAN

BY K. O. EMERY

ABSTRACT

The topography, composition, and water characteristics of the shallow platform surrounding Johnston Island were studied by aerial observation, diving, sounding, and sampling. The platform consists of highly permeable calcareous sediments and rocks similar to those of atolls. The peripheral reef, however, extends along only the leeward margin of the platform. Incompleteness of the reef may be due to partial erosion of an atoll during a glacial epoch of colder water and lowered sea level or to tilting of the atoll so that an original windward reef is now submerged, leaving only the present leeward reef above sea level. Refraction of waves around the platform and against the leeward reef produces a wave-driven current that moves easterly against both trade-wind and general oceanic current.

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INTRODUCTION

Johnston Island, one of the most isolated islands in the Pacific Ocean, lies alone at Lat. 16°44′ N., Long. 169°31′ W. in a large area of open ocean bounded by the Hawaiian Islands, the Line Islands, and the Marshall Islands. According to Leff (1940, p. 23–29) and Bryan (1942, p. 35–37) the annual Manila galleons passed close by Johnston Island during the sixteenth and seventeenth centuries, but the first recorded visit was that of the American

brig SALLY, which grounded on a shoal in 1796. In 1807 Johnston Island was visited by H. B. M. S. CORNWALLIS and named after her commanding officer, Charles J. Johnston. Shallow water east of Johnston Island was reported in 1897 by the master of the schooner NOVELTY, and the name Novelty Shoal was given (Anonymous, 1950, p. 176) though it is now little used. During 1923 U. S. S. WHIPPOORWILL and U. S. S. TANAGER made a survey of the island and surrounding shallow water (Gregory, 1924, p. 22), and Edwin H. Bryan, Jr. and other biologists accompanying the expedition collected and described the fauna and flora.

Aside from occasional guano-loading operations, little use was made of the island until about 1940 when civilian and military air travel enhanced the value of such stepping-stone islets as air strips. To facilitate landing of large airplanes the 3000-foot length of Johnston Island was doubled and a 44-foot hill (Bryan, 1942, p. 35–37) cut away. None of the original topography or shore remains. The smaller Sand Island, a mile northeast, has been less modified.

During and after World War II many scientists had brief glimpses of the 77-square-mile area of shallow water around Johnston Island during landings and takeoffs from the air strip, and some of them found time for collecting plants (Fosberg, 1949), corals (Wells, 1954, p. 402–404), fishes (Gosline, 1955), or making other observations. On each of several short visits the writer was impressed by the linear form of many shallow patch reefs, their reddish color (indicating abundant coralline red algae), and by the pattern of sand between the patch reefs showing direction of water current. These characteristics are quite different from those of the reefs and lagoons of the northern Marshall Islands (Emery, Tracey, and Ladd, 1954) and of Guam (Emery, in manuscript). An opportunity to study the area of Johnston Island between July 15 and 27, 1954 was provided by Office of Naval Research contract NR 081-217.

ACKNOWLEDGMENTS

The writer wishes to thank Col. V. J. Donahue, then commanding officer, for generous co-operation throughout; MSgt. B. P. Moran for taking underwater photographs; A/1c R. F. Silvers for aid in boat work; and many others on the island for help of various kinds. Dr. Maxwell S. Doty, University of Hawaii, made chlorinity analyses of water samples, and he and Drs. Harry S. Ladd and J. I. Tracey, Jr., U. S. Geological Survey, criticized the manuscript.

TOPOGRAPHY

Sources of Data

Information on the topography in the vicinity of Johnston Island was obtained from several sources. Chief of these is unpublished H. O. chart 5356, which contains about 2500 lead-line soundings made by the TANAGER expedition. Two echograms made by U. S. S. YUMA (TF 94) when entering and leaving the area on July 17 and 18, 1954 show topography directly south of the dredged channel between Johnston and Sand islands in more detail. These echograms (Pl. 2) reveal the presence of coral knolls rising above an otherwise gently sloping bottom at 4 to 10 fathoms, a topography similar to that in lagoons of atolls in the northern Marshall Islands. Reef outlines were taken mainly from an aerial photomosaic made in 1942 by Fleet Air Wing Two, partly from the old chart, and in a few instances from small aerial photographs made during the present study.

A new chart (Pl. 1) was compiled from all available data. The slope between 16 and 100 fathoms is steep, but between the reef edge on the west and 16 fathoms on the east is a broad gently sloping platform. Johnston and Sand islands are on the shallow west side of the platform.

Subdivisions

The area of Johnston Island and Sand Island is only about 0.35 square statute mile. Reefs exposed or nearly exposed at low tide comprise an area at least three times as great as the land, but exact measurement is difficult owing to the many small patch reefs. Most of the reef area, however, is in the main outer reef, which forms an arc about 9 miles long (Pl. 1). It is interrupted by a small boat channel west of Johnston Island and by a longer break near the northeastern end that separates the main reef from a

half-mile extension known locally as Small Island.

In a belt within about 2 miles of the main reef the bottom is shallow and marked by many elongate and subcircular patch reefs. Johnston and Sand islands also are in this belt. Because of its partial confinement between the main reef on the northwest and the islands and linear patch reefs on the southeast, the area is a distinct physiographic unit that will be termed the lagoon.

Most of the platform is east and southeast of the lagoon. It slopes toward the southeast from about 4 fathoms to about 16 fathoms, beyond which it steepens markedly. The average slope of the platform between 4 and 16 fathoms is 0.1°, in contrast to the 19-degree average slope between 16 and 100 fathoms. Many irregular hills and depressions are present. Elongate hills or ridges bordering the deep eastern end of the platform suggest submerged peripheral reefs.

Composition

General

A general impression of the composition of a shallow sea floor can be formed by examination of aerial photographs. The 1942 photomosaic covered only the shallow lagoon (area of Fig. 6); however, the base provided an airplane for making aerial photographs and visual observations of the entire platform. A flight pattern was set up consisting of 30-degree spokes radiating from a water tank in the northeastern part of the island. Vertical Kodachrome photographs were made from the open loading door at 20-second or 1350-yard intervals. At the flight elevation of 2000 feet, each photograph covers an area of 330 by 470 yards; thus, the 59 vertical photographs total about 3.0 square miles, or about 4 per cent of the platform. The bottom was visible to a depth of 15 fathoms, but the photographs are definitive only to about 10 fathoms.

At each photograph station visual estimates were also made of the number of tenths of the bottom area that was dominantly coralline algae (shallow reddish-brown patch reefs), coral (deeper and darker hummocky areas), and sand (smooth light-green areas between reefs). Later checking of the estimates by the photographs yielded similar results. Maps showing plotted estimates are cross-hatched where any component exceeds five-tenths of the area in a photograph (Fig. 1).

Surfaces of coralline algae dominate only along the main outer reef (Fig. 1; Pl. 3, fig. 1), although throughout the parts of the lagoon shallower than about 4 fathoms many patch reefs are topped by coralline algae. Many patch reefs are subround, and most are less than 50 yards in diameter (Pl. 3, fig. 2), though none appear to be streamlined like those reported by Newell (1956) at Raraoia Atoll in the Tuamoto Islands. Others form ridges as long as 500 yards that join in longer irregular curved patch-reef complexes (Pl. 1; Pl. 3, fig. 3, 4). No coralline algal patch reefs occur in the deep eastern part of the platform.

Areas judged to be dominated by coral occur throughout the lagoon and platform (Fig. 1; Pl. 3, fig. 2). However, coral may be more abundant than is suggested by aerial observation because coral forms much of the substrate of patch reefs that are topped by coralline algae and small pieces of coral occur in the sandy areas.

Sandy bottom is common in a strip extending along the length of Johnston and Sand islands, and in this shallow area many large dunelike waves have shapes that are controlled by currents (Pl. 3, fig. 3, 4). Sand also is dominant in the deeper areas on the eastern half of the platform.

Reefs

The clear warm water so promotes the investigation of submarine features by diving that it is difficult to force oneself to use other supplementary methods. Direct observation was much aided by MSgt. Moran and his underwater camera, a Ditto 99 enclosed in a plastic box of his own design. About 80 black and white photographs were exposed, selections of which are presented in Plates 4 and 5.

Several patch reefs were studied, and a profile of a typical one is shown in Figure 2. Characteristically they are topped with an irregular, overhanging surface of coralline algae just below the low-tide level. On the sides and locally beneath the algae are irregular masses of branching coral, mostly *Acropora*. The fringing lower

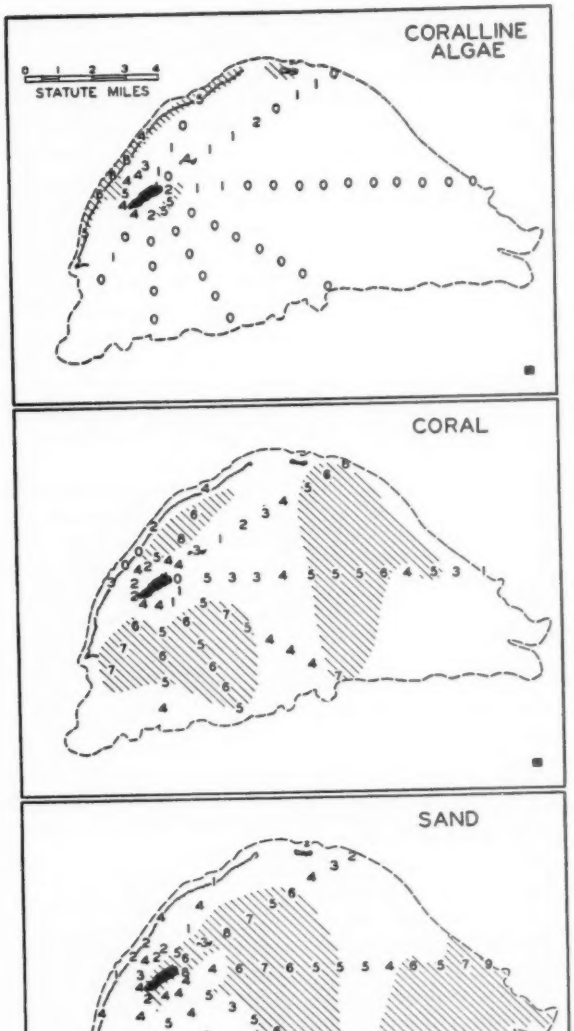

FIGURE 1.—COMPOSITION OF SHALLOW SEA FLOOR NEAR JOHNSTON ISLAND AS JUDGED FROM AERIAL OBSERVATION AND KODACHROME PHOTOGRAPHS

Reef boundary and 20-fathom contour (dash line) are shown. Size of area of each photograph indicated by black rectangles. Numbers indicate tenths (1 to 10) of the area of each photograph that consists of alga reef, coral reef, or sand bottom. Cross-hatching shows portion of platform that is dominated by each constituent.

slopes consist almost exclusively of loose pieces of dark-gray dead coral and dead coralline algae. Usually forming an abrupt angle with the loose talus is clean white sand on which large black holothurians are locally abundant.

veyor of small samples that stuck to tallow placed in a hole at the end of a lead sounding weight or from scratches made on the lead by hard bottom. Most (100) of the notations are of coral; the others are sand or coral and sand.

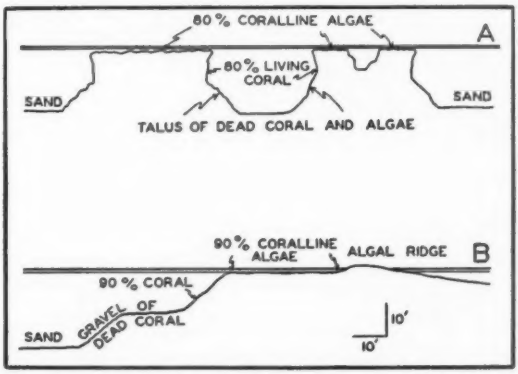

FIGURE 2.—PROFILE SKETCHES OF REEFS WITH RESPECT TO HIGH- AND LOW-TIDE LEVELS
A.—Isolated patch reef about 1 mile northwest of Johnston Island.
B.—Outer reef at Small Island.

The main outer reef was also examined at several places; a sketch is shown in Figure 2. Typically an algal ridge ("Lithothamnium" ridge) forms the outer edge. Seaward is a gentle slope that near the north end of the reef is cut by narrow grooves (Pl. 3, fig. 1). Lagoonward is a reef flat 40–150 yards wide, and composed chiefly of coralline algae but with small corals of various species (Wells, 1954) abundant in holes and small transverse channels (Pl. 4, fig. 3, 4). The lagoonward edge appears to be less commonly overhanging than on the patch reefs; instead, in several places there is a slope that consists largely of living coral with some dead coral and algae. Most spectacular of the corals is a form of *Acropora* (*A. hyacinthus*) that builds thin fragile circular brackets as much as 10 feet in diameter and commonly nested or tiered atop narrow pedestals (Pl. 5, fig. 3). At depths below about 15 feet dead coral commonly forms a ramp or a continuation of the slope to a flat bottom of sand 20 to 25 feet deep (Pl. 5, fig. 1, 2, 4).

Sediments

Chart 5356 contains 160 notations of bottom materials derived from examination by a sur-

In general, the notations show the presence of coral throughout the platform, but sand is dominant in deeper water to the east.

For more complete information on bottom materials it was necessary to collect new and larger samples. Specimens of coralline algae and coral were collected mostly by diving. For collecting sand at depths as great as 14 fathoms a light Van Veen-type dredge was lowered by hand on half-inch rope from a B-29 drop-boat with a 25-H.P. outboard motor. Positions were obtained by Brunton compass bearings to prominent structures on both islands.

The 62 samples are widely enough distributed to give a general picture of the composition of the sediments, but they are insufficient for determining distribution of algae and coral other than commonest species.

Composition of the 58 samples that contain sediment composed of organic debris was determined using the methods described by Emery (In manuscript) for Guam. The source organisms were identified by shape and mineralogy of the grains (Foraminifera and calcareous red algae being calcite; *Halimeda* and madreporarian coral being aragonite). The mineral form was determined by boiling in a solution of

TABLE 1.—SAMPLE POSITIONS AND COMPOSITION

Station	Latitude (north)	Longitude (west)	Depth (fathoms)	Field description		Percentage composition					
				Large pieces	Sediment*	Foraminifera	Shells	Fine debris	Halimeda	Coral	Coralline algae
1	16° 44.73′	169° 31.08′	3	.....	mud	0	1	97	0	0	2
2	44.80′	31.17′	3½	.....	fc sand	2	18	30	0	10	40
3	44.81′	31.21′	4	.....	fc sand	2	48	20	0	10	20
4	44.86′	31.26′	4	.....	fc sand	5	15	10	0	40	30
5	44.87′	31.28′	3½	algae	.....	..	..	..	..	..	..
6	44.92′	31.32′	3½	.....	fc sand	2	8	10	0	60	20
7	44.96′	31.40′	3½	coral	c sand	5	5	5	0	15	70
8	44.99′	31.44′	6	coral and algae	fm sand	2	8	10	0	70	10
9	45.05′	31.50′	3	.....	fm sand	1	7	22	0	45	25
10	45.11′	31.58′	2	.....	c sand, pebbles	5	5	0	0	15	75
11	45.17′	31.64′	1	.....	mc sand	1	4	0	0	40	55
12	45.22′	31.70′	0	coral	mc sand	1	4	0	0	25	70
13	44.83′	30.38′	1½	coral	c sand, pebbles	5	20	0	0	30	45
14	none	.....	...	.....	.....	..	..	..	..	..	..
15	46.82′	29.38′	3	coral and algae	c sand	0	3	0	0	17	80
16	47.51′	27.21′	3	coral and algae	mc sand	0	9	10	1	35	45
17	47.20′	27.90′	6	.....	mc sand	0	15	15	0	5	65
18	47.16′	28.17′	7	coral and algae	.....	0	25	0	0	5	70
19	47.13′	28.26′	5	.....	mc sand	0	35	0	1	14	50
20	47.05′	28.60′	6	.....	mc sand	0	10	0	0	10	80
21	46.90′	29.05′	5	coral and algae	c sand	1	14	0	0	5	80
22	46.75′	29.48′	3	.....	c sand	1	14	0	0	2	83
23	46.56′	30.00′	2	.....	c sand	1	4	0	1	34	60
24	46.48′	30.29′	2½	.....	mc sand	1	11	0	3	0	85
25	45.09′	30.42′	5	.....	f sand	5	10	15	0	40	30
26	44.11′	30.38′	7	.....	f sand	1	9	10	0	30	50
27	43.41′	29.60′	9	coral and algae	.....						
28	42.77′	28.90′	8	.....	f sand, mud	1	4	90	0	0	5
29	42.17′	28.10′	11	coral	crest—cs, peb. trough—mc sand	0 2	10 13	0 0	0 0	10 45	80 40
30	41.60′	27.44′	14	coral	c sand	10	5	0	0	20	65
31	41.78′	31.53′	12	.....	c sand	35	20	0	0	25	20
32	42.64′	31.50′	12	coral	mc sand	10	10	5	0	0	75
33	43.48′	31.52′	7	coral	mc sand	1	8	5	1	35	50
34	43.98′	31.45′	2	.....	mud	0	2	90	0	3	5
35	none	.....	...	.....	.....	..	..	..	..	..	..
36	44.12′	31.75′	2	.....	f sand	0	10	30	0	35	25
37	44.07′	32.03′	3	.....	fm sand	3	12	5	0	30	50
38	44.02′	32.27′	3½	.....	mc sand	2	8	0	0	45	45
39	44.00′	32.57′	3½	.....	c sand	0	5	0	0	25	70
40	43.75′	32.63′	3	algae	m sand	1	9	5	0	45	40
41	43.07′	32.80′	3	.....	c sand	1	8	5	1	35	50
42	43.28′	32.53′	1	.....	mc sand	0	15	0	5	25	55
43	43.52′	32.21′	1½	.....	mc sand	0	15	5	10	0	70
44	43.72′	31.86′	1½	.....	c sand	0	4	0	1	10	85
45	43.91′	31.75′	1½	.....	c sand	0	9	0	1	20	70

TABLE 1.—*Continued*

Station	Latitude (north)	Longitude (west)	Depth (fathoms)	Field description		Percentage composition					
				Large pieces	Sediment*	Foraminifera	Shells	Fine debris	Halimeda	Coral	Coralline algae
46	45.77′	30.83′	6	.....	m sand	1	13	10	1	15	60
47	46.17′	30.40′	7	algae	mc sand	1	14	0	0	45	40
48	45.80′	30.40′	4	.....	mc sand, pebbles	0	5	10	0	15	70
			4½	.....	pebbles	0	0	0	0	0	100
49	45.50′	30.40′	3½	.....	m sand	5	14	5	1	20	55
50	45.42′	29.62′	1	.....	mc sand	8	5	0	0	32	55
51	45.68′	29.20′	1½	.....	fm sand	2	7	5	1	5	80
52	45.68′	29.20′	2	.....	c sand, pebbles	0	10	0	0	15	75
53	45.68′	29.20′	0	coral algae	.....						
54	45.95′	28.80′	1½	.....	mc sand	2	13	5	0	15	65
55	44.68′	29.65′	7	.....	mud	0	5	85	0	0	10
56	44.85′	28.80′	6	algae	fm sand, pebbles	1	4	85	0	0	10
57	45.43′	28.15′	4	.....	fm sand, pebbles	1	4	70	0	15	10
58	46.00′	27.55′	8	.....	mud, sand	0	10	80	0	0	10
59	46.55′	26.94′	5½	.....	mud, sand	0	15	55	0	0	30
60	47.10′	26.32′	4½	algae	.....	..	..	..	..	..	..
61	46.50′	29.60′	1	algae	fc sand	0	15	0	0	20	65
62	44.41′	32.25′	2	.....	mc sand	1	8	0	1	20	70
Johnston Island			4			2	10	16	1	20	51
Simple average of all samples			(avg.)								
Guam (Cocos Lagoon)			1			3	15	8	11	45	18
Samples weighted by area of depth zones			(avg.)								
Bikini Lagoon			25			11	7	25	43	13	1
Samples weighted by area of depth zones			(avg.)								

*f = fine; m = medium; c = coarse; mud = silt and clay.

cobalt nitrate (Meigen's solution), which stains aragonite violet and does not affect calcite. Fragments of shells of pelecypods and gastropods may be either aragonite or calcite (or both), so identification of shells was restricted to recognition of shape or to presence of flat smooth surfaces. Material too fine-grained for identification of source organisms is classed as fine debris. Bulk percentages of the various constituents were estimated by examination with a binocular microscope. Comparison of the composition of sediments from Johnston Island with those from the lagoon of Bikini (Emery, Tracey, and Ladd, 1954, p. 62) and from the lagoon at the south end of Guam (Emery, in manuscript) shows the same major constituents but in different percentages (Table 1).

The dominant constituent of the sediments is coralline red algae comminuted to sand size. It is particularly abundant in samples near the main reef and comprises 50 per cent or more of the bulk of grains in most samples from depths less than about 4 fathoms except within about half a mile of Johnston Island (Fig. 3). Algal debris is abundant even in the deepest sample, 14 fathoms. Living masses were obtained at 9 fathoms, but at such depths the algae do not form the flat-topped patch reefs that characterize the lagoon west and north of Johnston Island. The higher concentration of coralline algal debris in the sediments at Johnston Island than at Guam and Bikini is doubtlessly a result

of the far more abundant algal patch reefs at Johnston Island.

The next most abundant constituent in the sediment samples is debris of coral. It occurs in nearly all samples, but is dominant in few (Fig. 3). Shell fragments also are spotty in their distribution. Foraminifera occur in most samples but usually only to a few per cent of all grains. Unlike at Bikini, *Halimeda* debris is rare in the sediment, never exceeding 10 per cent, and not observed in most samples.

Grains too small for certain identification, termed fine debris, are dominant in samples from just east of the lagoon. The position (Fig. 3) of most fine-grained sediments is such as might be expected if finer grains were winnowed from the shallow sandy lagoon floor and dropped when the easterly flowing currents reach deeper water east of the patch-reef complex. Possibly, some of this muddy sediment was freed by dredging operations in the lagoon northwest of Johnston Island.

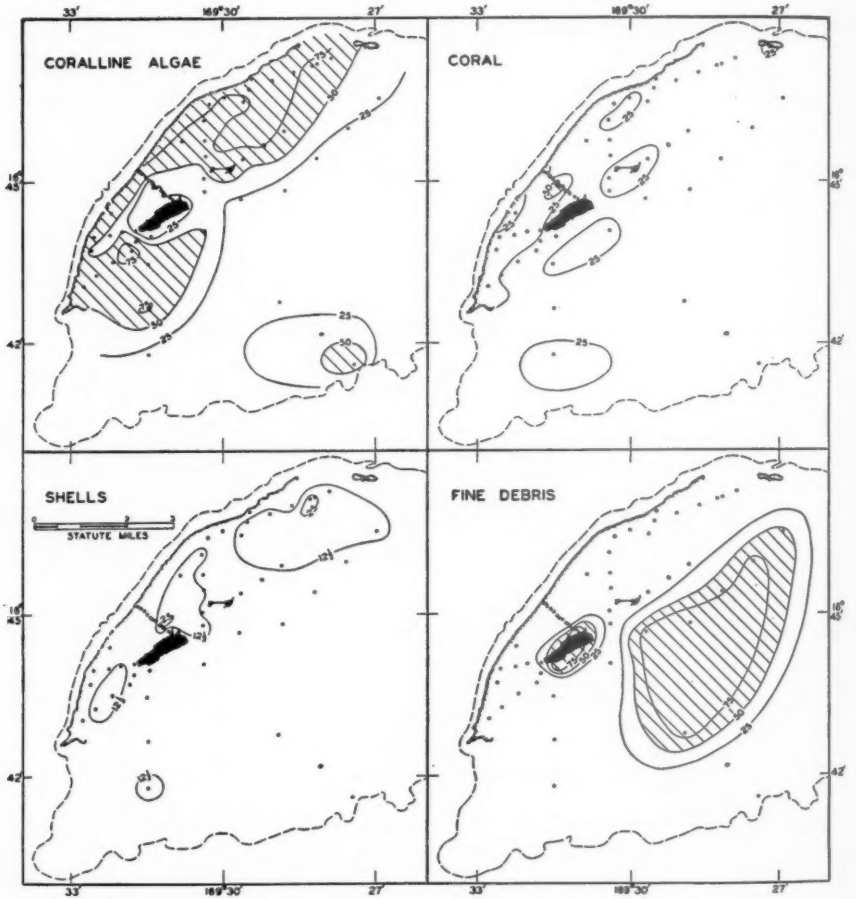

FIGURE 3.—MAPS SHOWING THE PERCENTAGE ABUNDANCE OF IMPORTANT CONSTITUENTS OF THE SEDIMENTS

Lines of equal abundance are drawn through the 25-, 50-, and 75-per cent values with cross-hatching in areas where each component exceeds 50 per cent of the bulk of grains in samples. The 20-fathom contour is shown by dashed line. Small circles mark sample positions.

Darwin (1887, p. 464), Cloud (1952, p. 26), Randall (1955), Newell (1956, p. 360, Pl. 43), and a few others have reported that fishes may be important in comminuting and transporting result in production and transportation of sediments in quantities that may rival the amounts produced and transported by waves and currents.

TABLE 2.—SEDIMENTS FROM INTESTINES OF FISHES

Per cent

	Sediment	Foraminifera	Shells	Fine debris	Halimeda	Coral	Coralline algae
Scarus perspicillatus (Steindachner) (parrot fish)	f sand	0	0	10	0	25	65
	f sand	0	0	10	0	0	90
Acanthurus fuliginosis Schultz and Woods (surgeonfish)	sand	0	1	19	0	35	45
	mud, sand	0	0	45	0	5	50
	sand	0	5	30	0	10	55
	mud, sand	0	0	40	0	0	60
	f sand	4	6	20	0	20	50
Melichthys radula Solander (trigger fish)	mud, sand	0	10	70	0	0	0
Arothron hispidus Linnaeus (puffer)	pebbles	0	30	0	0	30	40
	pebbles	0	5	0	0	5	90
	pebbles	0	15	0	0	20	65
	pebbles	0	40	0	0	60	0

sediments in reef areas, so an attempt was made to secure specimens of intestinal contents of various fishes for estimation of percentage contribution by various source organisms. Calcareous material was absent in several fishes that were speared, but two parrot fish contained sand consisting chiefly of coralline algae (Table 2). To help complete the picture samples of intestinal contents from surgeonfish, puffers, and a trigger fish from Palmyra Island (Supplied by Dr. E. Y. Dawson of University of Southern California) were analyzed. In these fishes as in the ones from Johnston Island debris from coralline algae and coral dominate. Shells are common only in the puffers, which contain the coarsest material, pebble size. Foraminifera and *Halimeda* were not present in these specimens but were reported from other fishes by Dawson, Aleem, and Halstead (1955), who described the soft portions of the intestinal content of fishes from Palmyra. The myriads of fishes that scrape and break off bits of coral and coralline algae during their feeding

Beach Rock

Beach rock (beach sand and gravel cemented by calcium carbonate) was not seen in place on Johnston Island owing to extensive artificial modification of the shore line. However, it is well exposed on Sand Island where it dips approximately southeast on all sides of the island, showing the former existence of an island that migrated southeastward and whose site is now marked by Sand Island. The beach rock is massive, but its surface is being eroded biochemically to form both the irregular topography of solution basins and the smooth water-level terraces (*see* Pl. 4, fig. 1). Erosion is accelerated by parrot fish that cut numerous pairs of small parallel scratches on the lower levels of beach rock (Pl. 4, fig. 2) with their projecting teeth while grazing for algae, according to observations made by MSgt. Moran and Dr. B. W. Halstead (Personal communications).

Records were obtained from Corps of Engineers Office in Honolulu of 56 borings made for foundations of 12 buildings well distributed

throughout the northeastern two-thirds of Johnston Island (Fig. 4). The deepest of these borings extends to 36 feet below mean low water. In addition, records of 6 wells ranging from 86 to 191 feet below mean low water were supplied by Sampson and Smock Drilling Co. of Honolulu. All records were drillers' logs and thus subject to misinterpretation. Thirty-nine of the borings encountered sandstone, presumably beach rock. In 18 the top of the sandstone was reported between +2.5 and +3.6 feet above mean low water and the bottom between +0.4 and −0.7 feet. In 10 others the top of the sandstone was between −4.3 and −6.4 feet. Thus, there may be two layers of beach rock beneath Johnston Island. The upper layer is doubtlessly the one that is widespread in the wave-washed zone of most tropical islands (including Sand Island) and penetrated by 5 test wells drilled on Bikini Island. Support for the second deeper layer is given by samples of beach rock collected 8 feet below sea level along the bases of the linear and roughly parallel algal reefs that extend between Johnston and Sand Islands (Pl. 1; Pl. 3, fig. 3). It is believed that the unusual straightness of these patch reefs is a result of growth of coralline algae atop the outcropping edges of the presently submarine beach rock.

The records of deeper parts of the wells show alternating sand, loose coral and sand, and coral; there is little certainly of correlation from well to well. Mud of unknown origin was reported in several wells. Noncalcareous rock was not reached.

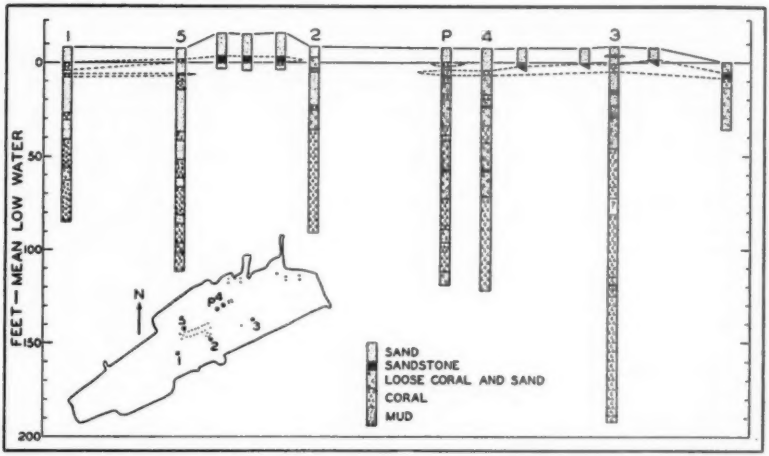

FIGURE 4.—DRILLERS' LOGS OF FIRE WELLS AND FOUNDATION TEST BORINGS PROJECTED TO A LINE THROUGH THE LONG AXIS OF JOHNSTON ISLAND

Notations of shallow hard ledge coral in fire wells and of sandstone in foundation borings are believed to indicate beach rock, the possible correlation of which is indicated by dash lines. On insert map, numbers show fire wells and dots show test borings.

OCEAN WATER

Surface temperature of the water was measured at 20 well-distributed stations, but no geographical variation could be determined. Instead, there proved to be a diurnal cycle in which the temperature of the lagoon and reef complex presented an average increase from 81.5°F. at 0930 local time to 82.8°F. at 1500. Temperature of surface water in the deeper platform east and south of the islands showed a similar diurnal increase, but values were about 1°F. lower. The daytime water temperatures lie in the range between daily mean and daily maximum air temperatures, 81° and 85°F., respectively (Fig. 5).

Chlorinity of surface water showed neither a geographical nor a diurnal trend. Values ranged

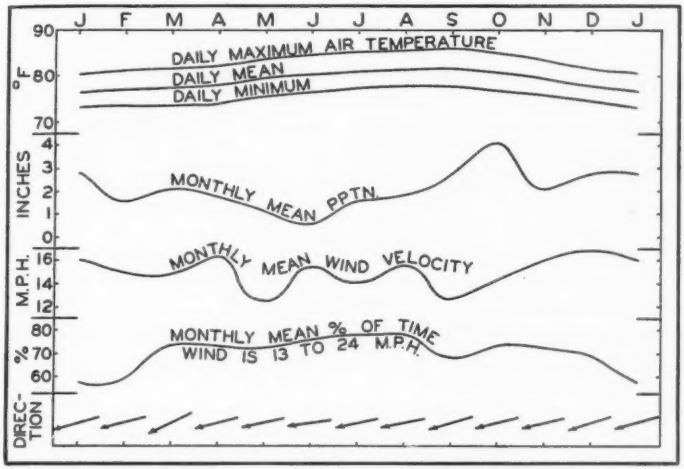

FIGURE 5.—METEOROLOGICAL SUMMARY

Based on data collected at Johnston Island by base meteorologist March 1945 to December 1951. Note the small annual range of temperature, high average wind velocity, and the constancy of wind direction.

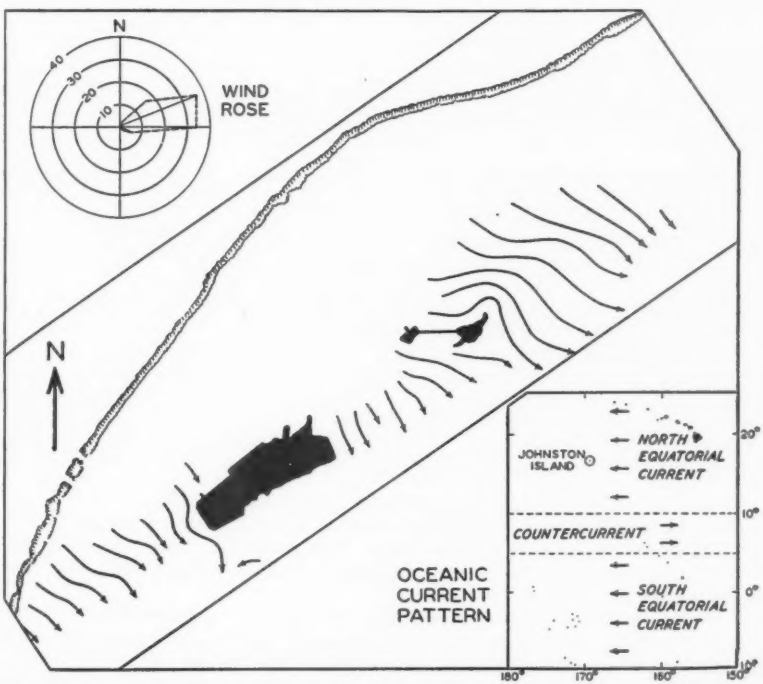

FIGURE 6.—FLOW LINES OF WATER AS JUDGED FROM TOPOGRAPHY OF SAND BOTTOM SHOWN ON AERIAL PHOTOMOSAIC

Spacing of lines is arbitrary and does not indicate relative velocity. Wind rose (showing direction *from*) in upper left-hand corner is compiled from data collected at Johnston Island March 1945 to December 1951. Generalized current diagram at lower right-hand corner is from various sources.

from 19.15 to 19.34‰, with an average of 19.27‰, corresponding to a salinity of 34.81‰.

Johnston Island is in the zone of the North Equatorial Current (lower insert, Fig. 6), a belt of water nearly 1000 miles wide and several hundred feet deep moving westerly at speeds up to about half a knot and forming the southern side of a large clockwise gyral that encompasses the whole North Pacific Ocean. During the travels of the water it accumulates and carries various kinds of debris. From March 1953 to October 1953 several hundred pounds of pumice were deposited on the north shores of Johnston and Sand islands. These were well-rounded pieces up to 3 inches in diameter. The greatest quantities arrived in September and October 1953 when it was so abundant that screens and pipes of the water evaporators became filled with pebbles. Although pumice is not uncommon on coral islands (Sachet, 1955), the sudden arrival of large quantities on Johnston Island suggests a relationship of the pumice to volcanism at San Benedicto Island off Mexico, which began August 1, 1952 (Richards and Dietz, in press), or to Myojin Reef off Japan, which began September 1, 1952 (Dietz and Sheehy, 1954). The only other erratic noncalcareous rock in the area (other than those brought by man) is a 30+ cm. piece of hard fine-grained rhyolite embedded in beach rock at Sand Island that was found by Dr. Maxwell S. Doty. Perhaps it was rafted to the island by driftwood floating in the North Equatorial Current (Emery, 1955), or was part of a ship's ballast.

Currents in shallow water at both ends of Johnston Island were measured several times by estimating the distance that fluorescene-dye marker thrown onto the water traveled in 1 minute. Results showed a tidal variation with average velocities of half a knot to the northwest at flood tide and of 1 knot to the southeast at ebb tide. The current pattern is well shown by the effect of moving water upon the distribution of sand near patch reefs. These patch reefs block the current, causing sand to be deposited against the currentward side and leaving a depression where the water speeds through gaps between the patch reefs. Examination of several such areas showed depths in the gaps to be about half a fathom deeper and floored with coarser sediment than the adjoining areas (Table 1, samples 51, 52). Owing to greater depth in gaps between patch reefs, photographs show those places to be darker (Pl. 3, figs. 3, 4). Many such contrasts are

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PLATE 2.—ECHOGRAM ALONG NORTH-SOUTH TRAVERSE TO CHANNEL BETWEEN JOHNSTON AND SAND ISLANDS

Supplied by Lt. D. A. McMinn, commanding officer, U. S. S. YUMA (TF 94). Top three sections (made at 9.6 knots approaching Johnston Island) are in sequence: left end of top section joins right end of second; left end of second section joins right end of third; left end of bottom section (made at 1.9 knots leaving Johnston Island) joins left end of third section. The evenly spaced minor irregularities in the bottom section were produced by lifting and dropping of the ship by the waves. Horizontal lines are at 5-foot intervals; curves are at 20-second time intervals. Long. 169° 30.4′ W.

PLATE 3.—AERIAL PHOTOGRAPHS OF REEFS

FIGURE 1. MAIN OUTER REEF NEAR SMALL ISLAND

Coralline algae comprises the broad light area near the breaking waves and the darker splotches in lower left. Lighter areas in lower left are sand pockets. Surge channels are absent, but grooves are present seaward of breaking waves. Note refraction of waves that makes acute angle toward lower right (east). Elevation, 2000 feet. Area, 300 by 440 yards.

FIGURE 2.—SUBROUND PATCH REEFS NORTHEAST OF JOHNSTON ISLAND

Top of patch reefs is coralline algae. Deeper anastomosing reefs, largely of coral, partition off small patches of sand. Elevation, about 500 feet. Bottom edge is about 90 yards.

FIGURE 3.—LINEAR PARALLEL PATCH REEFS BETWEEN JOHNSTON ISLAND AND SAND ISLAND

Top of reefs is coralline algae. Note shading of intervening areas of sand that show current flow toward lower right (east); dark areas are deeper than light ones. Elevation, 2000 feet. Area—300 by 440 yards.

FIGURE 4.—LINEAR IRREGULAR PATCH REEFS NORTH OF JOHNSTON ISLAND

Top, composed of coralline algae, clearly overhangs sides. Intervening areas of sand show current markings. Elevation, about 300 feet. Bottom edge is about 50 yards.

ECHOGRAM ALONG NORTH-SOUTH TRAVERSE TO CHANNEL
BETWEEN JOHNSTON AND SAND ISLANDS

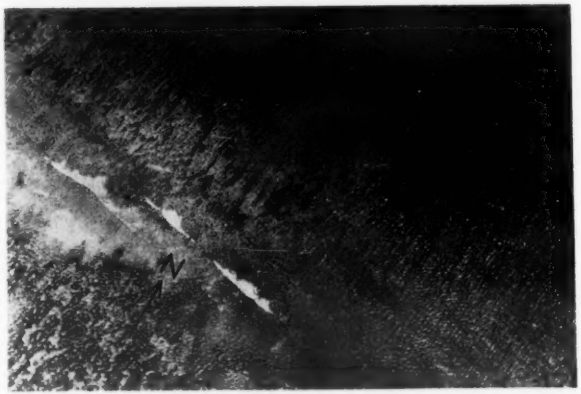

FIGURE 1

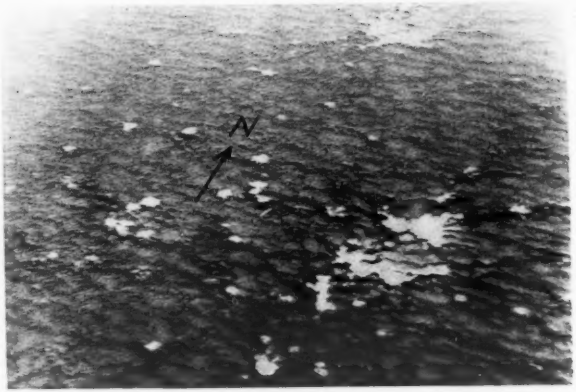

FIGURE 2

FIGURE 3

FIGURE 4

AERIAL PHOTOGRAPHS OF REEFS

FIGURE 1

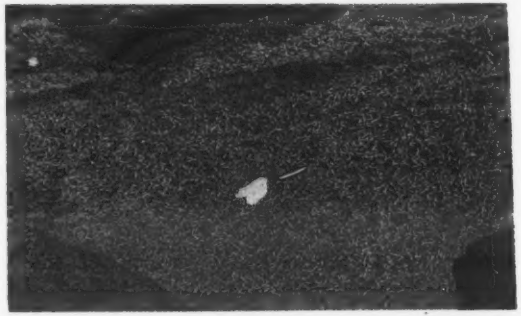

FIGURE 2

FIGURE 3

FIGURE 4

SHORE AND REEF FEATURES

FIGURE 2

FIGURE 4

FIGURE 1

FIGURE 3

UNDERWATER VIEWS OF SIDES AND BASES OF REEFS

visible on the 1942 photomosaic in areas where the depth is less than about 2 fathoms and where both patch reefs and sand bottom are present. Lines of flow interpreted from the mosaic are shown by Figure 6. The spacing of lines is arbitrary, no velocities being portrayed. Evidence from the aerial photographs supplements the current measurements in showing a predominant movement of water away from the reef and against the steady trade wind and the North Equatorial Current (Figs. 5, 6). This current must be a result of the driving of water across the reef by waves that have become refracted around the whole platform of Johnston Island so that they move eastward against the trade wind. Similar piling up of water atop a reef by wave pressure was observed at Bikini (von Arx, 1954). At flood tide, however, the mass of water that must enter the lagoon is evidently greater (mean tide range is 1.9 feet; diurnal range is 2.2 feet) than can be supplied by wave pressure, so the current near Johnston Island is reversed to flow for a time northwestward into the lagoon.

Ground Water

Five of the deep wells 18 inches in diameter are kept available for water supplies in event of fire. Their presence 450–580 feet from shore (Fig. 4) suggested a means of estimating the permeability of the island's substrate.

Curb elevations with respect to a bench mark on the wharf (tied to mean low water) were determined with a level to within an accuracy of 0.005 inch. Depths to water table below the curbs were measured at 1- to 3-hour intervals during a 30-hour period. At the same time a tide staff on the wharf was read. The results (Fig. 7) show a very close correlation of tide in the wells with that of the lagoon. The amplitude in the fire wells is about 80 per cent of that in the lagoon (Table 3) with greatest departures at low tide. Period lag is not recognizable except during the low tide of July 24 when it ranged from 0 to 30 minutes behind the lagoon tide. Both the high amplitude and the slight lag indicate a high permeability of the sediment and rock beneath the island, much higher than that found by McKee (1956) by similar measurements at Kapingamarangi Atoll in the Caroline Islands. Comparison at high and low tides shows that the water in the wells averages from 0.095 to 0.340 feet above that in the lagoon. The water level in the wells does not necessarily mark the top of the Ghyben-Herzberg lens, because the wells are cased to an unknown depth and the thickness of brackish water in them may be independent of that in the lens outside the wells.

Plate 4.—SHORE AND REEF FEATURES

Figure 1.—Massive Beachrock at Sand Island
Erosional features of solution basins at upper left, and water level terrace in foreground.
Figure 2.—Beachrock of Water-Level Terrace on Sand Island
Showing pairs of parallel scratches made by teeth of grazing parrot fish.
Figure 3.—Surface of Main Reef 2¼ Miles West of Small Island
Looking along 2-foot-wide channel lined by *Acropora* and *Porites*, and with floor of coral gravel
Figure 4.—Lagoonward Top and Slope of Main Reef at Point 2 Miles West of Small Island
Surface is mostly coralline algae

Plate 5.—UNDERWATER VIEWS OF SIDES AND BASES OF REEFS

Figure 1.—Coral Gravel Terrace at Lagoon Side of Main Reef 2 Miles West of Small Island
Slope up to reef is at right. Depth is about 10 feet.
Figure 2.—Contact Between Gravel and Sand Bottom About 75 Yards Lagoonward from Main Reef 2 Miles West of Small Island
Pipefish is about 5 feet long. Depth is 16 feet.
Figure 3.—Slope of Coral Knoll About 50 Yards Lagoonward of Main Reef 2 Miles West of Small Island
Acropora disk in foreground is about 6 feet in diameter; bottom one at right is 10 feet. Depth is 12 feet.
Figure 4.—Base of Patch Reef at Point 1¼ Miles North of Sand Island
Porites colony is on right. Flat bottom is sand with scattered coral gravel near reef and small separate coral colonies in distance. Depth is 15 feet.

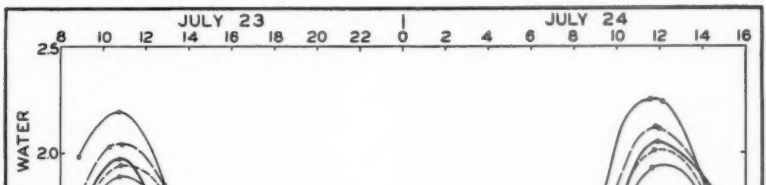

FIGURE 7.—TIDE CURVES FOR OPEN FIRE WELLS AND FOR LAGOON AT JOHNSTON ISLAND
Tide height versus time in hours. Data is relative to mean low water

TABLE 3.—TIDE IN WELLS AND LAGOON

Well no.	Distance from shore in feet	Original depth of well below curb in feet	Elevation of curb in feet	Range of tide in feet	Per cent range of lagoon tide	Average height above lagoon tide in feet	Chlorinity ‰ 4 feet below water surface
1*	550	94	8.59				17.452 (after pumping)
2	510	100	8.69	1.39	82	0.095	3.964
3	510	200	8.71	1.50	88	0.335	1.227
4	450	130	7.93	1.23	69	0.340	1.905 (oily)
5	580	120	7.79	1.21	71	0.250	8.410
p†	450	127					19.158 (after pumping)
lagoon				1.78	100		19.272 (average)

* Capped during survey.
† Priming well, pump attached.

SUMMARY AND CONCLUSIONS

The platform atop which Johnston Island is situated is similar to atolls of the Marshall and other groups in the Pacific Ocean in some respects and it differs in others. The main outer reef has a typical cross section with a sequence of a gentle slope cut locally by grooves, an algal ridge, and a reef flat. Steep coral knolls dot the area of deeper water south and east of the islands. The composition of the platform is generally similar to that of atolls, with masses of coralline algae and coral supplying debris for sediments. Shells, Foraminifera, *Halimeda*, and debris too fine to classify as to source are represented. Locally derived detrital minerals and rocks are absent, and basement is at least 200 feet below sea level.

The chief difference between the Johnston Island platform and typical atolls is that the main outer reef extends around only one-fourth the circumference of the platform. In addition,

the platform is very shallow within a 2-mile belt bordering the main reef. In this belt are the only land areas plus numerous patch reefs topped by coralline algae.

Two explanations seem worthy of consideration: (1) removal of a windward reef by erosion, and (2) tilting of a former typical atoll southeastward. According to the erosional explanation, an original outer reef that was most exposed to large waves from the east may have been eroded away when reef growth was less vigorous than now, perhaps during a glacial epoch of colder than normal ocean water standing at a lowered level. This explanation is strengthened by the fact that Johnston Island is near the northern limit of atolls in the Pacific Ocean. When only the leeward outer reef remained, it served as the chief source of sediments that were carried eastward by currents driven by pressure of refracted waves possibly supplemented by transportation by fishes. These sediments could perhaps account for the sloping surface and for burial of a possible submerged sea cliff across the platform.

Alternately, the platform may have been tilted southeastward. Support for this explanation is given by the presence of ridges that fringe the deep eastern margin of the platform, rising 4 to 8 fathoms above the adjoining platform, approximately the same as the height of the existing main outer reef above the adjoining lagoon floor. The tilt may also have raised the northwestern side of the platform, accounting for the shallow lagoon in that area.

Under present climatic conditions reef growth is much more vigorous on the windward than on the leeward sides of atolls so that a windward reef eroded away during a glacial epoch should perhaps have been replaced by a new one developed when the ocean warmed and sea level rose again. If the windward reef had been suddenly submerged to its present depth by tilting, a long time would be required for it to grow upward to the present ocean surface. Insufficient data are available for determining the more probable of the two explanations for the incomplete outer reef though the author slightly favors the second one. More complete sounding and sampling of the eastern margin of the platform plus the possible tracing of terraces around the slope below the platform might provide critical information on the history of the Johnston Island platform.

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University of Southern California, Los Angeles, Calif.

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FAULT IN PALEOZOIC ROCKS NEAR FREDERICK, MARYLAND

BY R. B. HOY AND R. L. SCHUMACHER

ABSTRACT

Diamond drill cores from an area 5 miles southwest of Frederick, Maryland, reveal significant stratigraphic and structural information.

The Antietam and Tomstown (Lower Cambrian) and Grove formation (Ordovician) are involved. The Antietam has some quartzite layers but is predominantly quartzose phyllite. The lower 40 feet of Tomstown is dolomite with sericite partings. The remaining 140 feet is impure, thin-bedded dolomitic limestone. The Grove is a light-gray slightly dolomitic limestone with red staining in the matrix of breccias and along fractures. The Antietam and Tomstown dip easterly 25°–30°. Overlying the Tomstown, above a fault which also dips 25°–30° easterly, is Grove limestone which is overturned, dipping 75°–85° easterly.

Along the fault are up to 5 feet of black clay gouge, 30 feet of breccia, and slickensides. The absence of the Frederick limestone and the angular relationship of the Grove bedding to the fault surface provide additional evidence of faulting. The fault, having younger rocks resting on older, could be normal, but the low angle plus overturning of the Grove limestone suggest a subsequent shear thrust.

The authors postulate that this fault or a series of similar faults may explain anomalous stratigraphic relations in the Lower Paleozoic rocks along the eastern edge of Catoctin Mountain. Locally, where the Antietam and/or Tomstown formations are missing, faulting could be the cause instead of facies changes or one or more unconformities.

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INTRODUCTION

In an exploration project near Frederick, Maryland (Fig. 1), diamond drilling revealed information pertinent to understanding the structure of the area. Drill holes were located so as to penetrate the mapped location of the Triassic border fault (Jonas and Stose, 1938; Whitaker, 1955). However, instead of penetrating Triassic rocks, the drilling encountered Paleozoic rocks; moreover, a low-angle fault was located within the Paleozoic.

Whitaker (1955, p. 448–450) discusses the anomalous stratigraphic relationships involving the Harpers, Antietam, Tomstown, and Frederick formations along the eastern slope of Catoctin Mountain. He presents the following stratigraphic columns to illustrate the difference between the sequence of the Chilhowee group and the overlying carbonate rocks in the

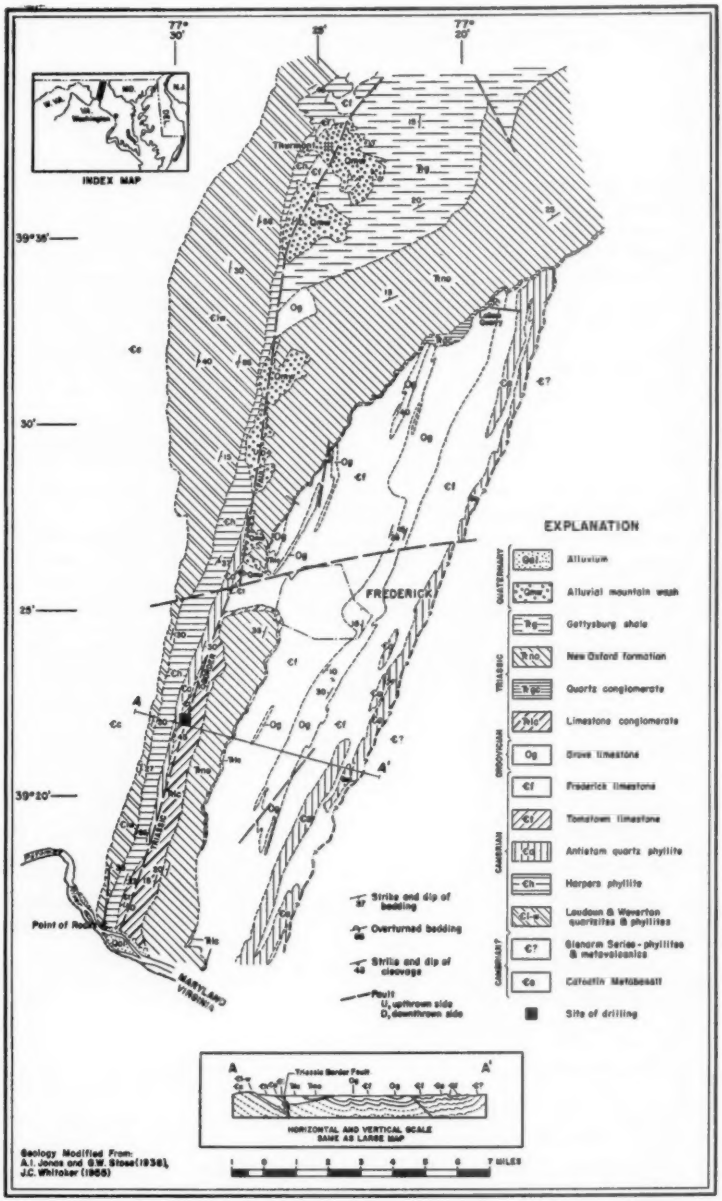

FIGURE 1.—GENERALIZED GEOLOGIC MAP OF CENTRAL MARYLAND

South Mountain and Great Valley area and the comparable sequence in the Catoctin Mountain and Frederick Valley area:

SOUTH MOUNTAIN
Great Valley Area

UC Conococheague limestone
MC Elbrook limestone
LC Waynesboro dolomite and shale
Tomstown dolomite
Antietam quartzite
Harpers phyllite

CATOCTIN MOUNTAIN
Frederick Valley Area

UC Frederick limestone
LC Tomstown dolomite (Locally absent)
Antietam quartzite (Locally absent)
Harpers phyllite

At Thurmont to the north, Harpers phyllite is overlain by Frederick limestone. West of Frederick, the Harpers is overlain by Antietam quartzite. North of the Potomac River, the Harpers is overlain by Tomstown dolomite. South of the Potomac in Loudoun County, Virginia, the Harpers is overlain by Antietam quartzite. According to Whitaker several hypotheses may explain the anomalous relationships: (1) faulting, (2) facies change, or (3) one or more unconformities. He reasons that faulting is unlikely as no faults have been observed between the Harpers and the overlying Cambrian carbonate formations. Furthermore, near Thurmont, Frederick limestone overlies Harpers phyllite in a tight syncline, which would require the hypothetical fault to be prefolding, a condition Whitaker says is unknown in the South Mountain province.

The definite evidence of faulting, as established by drilling, requires that faulting be considered as a possible explanation for the anomalous stratigraphic relationships.

ACKNOWLEDGMENTS

The writers thank the officials of The New Jersey Zinc Company for releasing the information for publication. W. H. Callahan suggested that the information was of sufficient interest to warrant publication and offered helpful suggestions. Constructive critical reading of the manuscript by Ernst Cloos, Marland P. Billings, and John C. Whitaker is gratefully acknowledged. Ernst Cloos and R. M. Foose corroborated identification of the Grove limestone. A. H. Willman, N. N. Moebs, and J. E Clark drafted the figures.

DIAMOND DRILL HOLE DATA

The drilling site is 5 miles southwest of Frederick, Maryland, and 1 mile south of U. S. Highway 340 as measured along the mapped location of the Triassic border fault (Figs. 1, 2).

Four drill holes on one transverse section penetrated a fault. Two other holes on a parallel section 600 feet to the north were drilled through the brecciated zone in the footwall of the fault.

Upon the first penetration, the structure was thought to be the Triassic border fault, because the red color and the fragmental character of the rock on the east side resembled the Triassic limestone conglomerate. As more data were available the hanging-wall rock was identified as gray Ordovician Grove limestone, locally brecciated and stained red; the fault proved to be low angle and is believed to be a Paleozoic thrust.

STRATIGRAPHY OF THE DRILL CORE

Description of Core

Three distinctive rock types were encountered in drilling: (1) quartzose phyllite, (2) sericitic limestone or marble, and (3) limestone and limestone breccia conspicuously stained red along fractures and in the matrix of the breccia. These rocks are believed to belong to the Lower Cambrian Antietam and Tomstown formations and to the Ordovician Grove limestone respectively. The Upper Cambrian Frederick limestone which normally underlies the Grove limestone is absent.

Lower Cambrian System

Antietam formation.—The Antietam formation, the uppermost of the Lower Cambrian clastic series, was encountered in the deeper portion of each hole. The deepest penetration

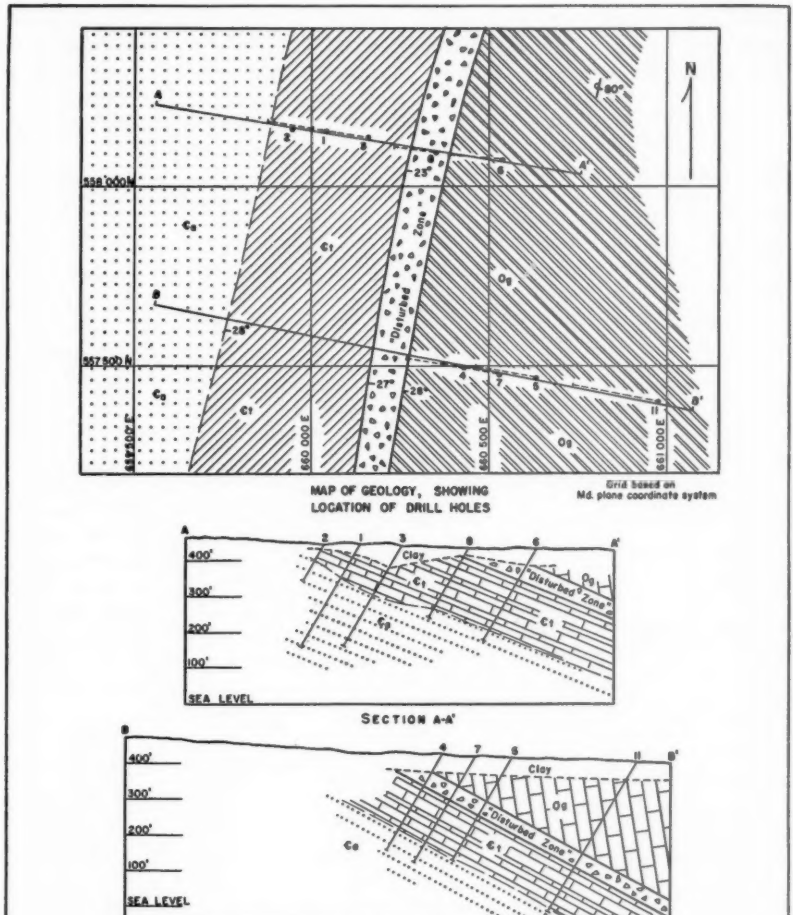

FIGURE 2.—GEOLOGIC MAP AND SECTIONS SHOWING LOCATIONS OF DRILL HOLES

was 225 feet in hole No. 1. The rock is brown, brownish-gray, or greenish-brown quartzose phyllite or quartz-mica schist, with occasional layers of bluish-gray quartzite. Bedding is almost obliterated by well-developed cleavage.

Stose and Stose (1946, p. 42) estimate the thickness of the Antietam to be about 300 feet.

Tomstown formation.—The Tomstown forma-

tion is the lowermost Cambrian carbonate rock. It is light- to dark-gray, finely to medium crystalline, thin-bedded to massive limestone and dolomite with sericitic and carbonaceous partings.

The Tomstown is 180 feet thick as determined by drill data; the lower 40 feet is a white to light-gray, medium- to fine-grained, massive to thin-bedded dolomite with minor sericite partings. The upper 140 feet, immediately under the fault, consists of gray, thin-banded dolomitic limestone with numerous sericite and carbonaceous partings. In near-by areas it is 1000 to 1500 feet thick (Stose, 1932, p. 49; Cloos, 1941).

Ordovician System

Grove formation.—Overlying the fault is the Ordovician Grove limestone. It is predominantly a light-gray (with a reddish tinge), finely crystalline, slightly dolomitic limestone. Irregular splotches and anhedra of red calcite are abundantly scattered through much of the rock. Some of the rock is brecciated with light-gray dolomitic limestone fragments in a ferruginous red limestone matrix.

Following is a detailed description of the Grove limestone cored in drill hole No. 11:

Partial Stratigraphic Section of Grove Limestone Measured in Drill Hole No. 11

	Thickness Feet
Gray, locally red, medium-bedded, fine-grained limestone with local shale partings.	20
Gray (with faint reddish tinge), thick-bedded, fine-grained limestone with local red calcite anhedra up to 1 inch by ¼ inch. 1½ feet contains scattered sand grains.	13
Gray, subangular, fine-grained, limestone fragments in a red, medium-bedded limestone matrix.	4
Gray, faintly thin-bedded, fine-grained limestone with red calcite anhedra elongate along bedding up to 1 inch by ¼ inch.	4
Gray (becoming reddish gray toward bottom), medium- to thin-bedded, fine-grained limestone with limestone breccia.	24
Gray, locally reddish, thin-bedded, fine-grained limestone with local black shale partings and local limestone breccia.	10
Gray, fine-grained, subangular, limestone fragments in a red, fine-grained limestone matrix.	22
Gray, massive, fine-grained limestone with local pisolitic texture and red calcite anhedra.	36
Gray, angular limestone fragments in red, medium-bedded, fine-grained limestone matrix.	17
Total thickness	150

The rock is believed to be Ordovician Grove limestone, in part infiltrated and stained red by meteoric water circulating from superjacent Triassic red shale and limestone conglomerate.

The most convincing argument for naming the rock in the hanging-wall block of the fault Grove limestone is the striking similarity between this rock and accepted Grove limestone observed in a quarry at LeGore, Maryland (brought to the writers' attention by Cloos). As illustrated by Stose and Stose (1946, p. 47–48), a cross-fault strikes E.–W. in this quarry. Specimens from the fault zone along the east wall of the quarry match every type of rock exhibited in the hanging-wall core. The Triassic overlap projects over this quarry about 800 feet above the present surface. Yet within the fault zone a red stain has infiltrated the fractures, the matrix of fault breccias, and some of the relatively unbroken rock.

Similar material is found in the Thomasville Stone and Lime Company Quarry, several miles west of York, Pennsylvania (brought to the writers' attention by Cloos). At this locality, Kinzer (Cambrian) limestone has been stained red, presumably by percolation of waters along fault zones to a depth of more than 500 feet below the projected overlap of the Triassic. This fault breccia also resembles the hanging-wall rock, but not so closely as does the Grove limestone at LeGore.

Structure

General Statement

Keith (1893) and Jonas and Stose (1938) depicted Catoctin Mountain as a syncline overturned to the west, whereas Whitaker (1955) following Cloos' mapping of the South Mountain fold (1941; 1946; 1947; 1951) mapped it as a tightly folded sequence dipping eastward forming the east limb of the South Mountain

anticlinorium. Whitaker's interpretation required revision of the stratigraphy. What Jonas and Stose (1938) mapped as Loudoun on the east side of Catoctin Mountain is actually a zone of uppermost Weverton and the basal tailed information corresponds well with the details of Whitaker's map (1955, Pl. 1) and fits the Whitaker interpretation that Catoctin Mountain is the east limb of the South Mountain fold.

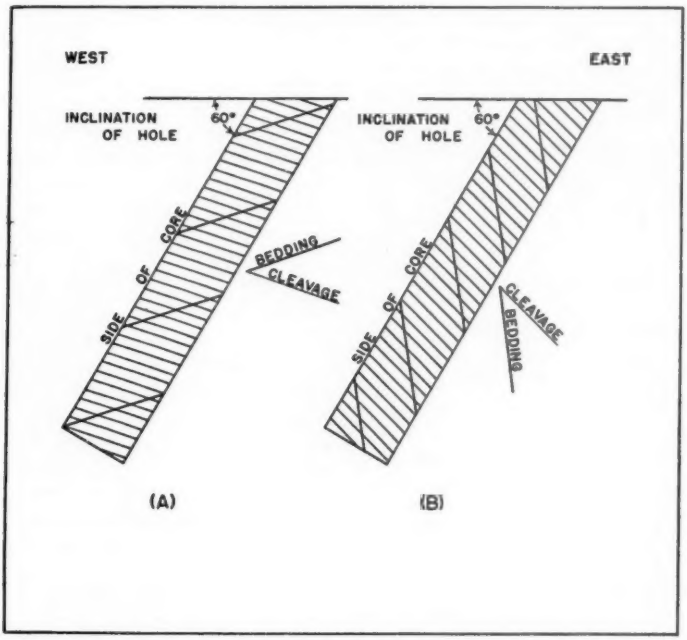

FIGURE 3.—SKETCH OF DRILL CORE SHOWING POSSIBLE COMBINATIONS OF CLEAVAGE AND BEDDING IN GROVE LIMESTONE
Assuming northward strike. (A) Bedding 20°W., Cleavage 15°E. (B) Bedding 80°E., Cleavage 45°E.

Harpers. The need for the fault Jonas and Stose (1938) mapped between Loudoun and Harpers is therefore eliminated. The writers mapped Catoctin Mountain and the adjacent part of Frederick Valley from Frederick to the Potomac River; their mapping supports Whitaker's interpretation.

Detailed Structure Determined by Drilling

The Lower Cambrian rocks, including the Antietam and Tomstown formations, were penetrated by all the drill holes. The bedding strikes N. 15° E. and dips 25°–30° SE. Fold axes are horizontal, and axial planes, as indicated by flow cleavage and drag folds, also strike northerly and dip 40°–50° E. This de-

Three drill holes (Fig. 2, Section B-B′) encountered Grove limestone in the hanging wall of a low-angle fault. Most of the bedding is at an angle of 45° to the axis of the core. Thin sections of core, oriented at right angles to bedding, indicate the bedding is 35° and the flow cleavage 75° from the core axis. The hole is inclined 60° westerly. Assuming a northerly strike for bedding and cleavage, the dips would have to be one of the following combinations (Fig. 3): (1) bedding 15°–25° W., cleavage 15° E.; (2) bedding 75°–85° E., cleavage 45° E.

Combination (1) would fit the bedding-cleavage relationship in the upper limb of a west-folded recumbent anticline, whereas (2) satisfies the requirements for the westerly overturned limb of an asymmetrical anticline.

FIGURE 4.—DIAGRAMS ILLUSTRATING THE DEVELOPMENT OF THE STRUCTURES INVOLVED IN THE THRUST FAULT

(A) Asymmetrically folded Paleozoic sediments; (B) Folded sediments offset by a subsequent shear thrust; (C) Pre-Triassic erosional surface developed on folded and faulted sediments; (D) Present erosional surface following deposition of Triassic sediments and offset along Triassic border fault

Numerous examples of the latter exist in Catoctin Mountain west of Frederick (Whitaker, 1955, Pl. 1) and in Sugarloaf Mountain 9 miles south of Frederick (Scotford, 1951, Pl. 1), whereas the former are rare (the senior author has observed small recumbent folds in the Catoctin formation in Virginia south of Point of Rocks, Maryland). Because combination (2) is much more common, the overturned attitude of the Grove limestone as shown in Figure 2 (B) is tentatively accepted.

Drill-core information proved the existence of a low-angle fault between the Tomstown formation and the Grove limestone. Features demonstrating the fault are 5 feet of black clay gouge, 30 feet of fault breccia, slickensides, the absence of the Frederick limestone, and the angular relationship of bedding in the Grove limestone to the contact with underlying Tomstown.

This low-angle fault with younger rocks resting on older could be either a normal fault, possibly a spur from the Triassic Border fault, or a thrust fault. The low angle suggests thrust faulting (Billings, 1942, p. 192). The age relationships, younger rocks on older, suggest normal faulting, but as Billings demonstrates (1933, p. 140–165) younger rocks may be thrust over older rocks. Following Billings' (1942, p. 172–175) terminology, the fault, if a thrust, is a subsequent shear thrust probably initiating as stretch thrust. Figure 4 illustrates the probable mechanics of thrusting. The structural-stratigraphic relationships revealed by drilling are illustrated by the positions of the Antietam, Tomstown, and Grove formations at the left edge of Figure 4D. The authors believe the fault is a subsequent shear thrust.

Conclusions

(1) Brecciated and fractured Paleozoic Grove limestone has been stained red, presumably by percolating meteoric waters circulating from superjacent Triassic red shale and limestone conglomerate.

(2) The structures of the Tomstown and Antietam formations fit the interpretation that Catoctin Mountain is the east limb of the South Mountain anticlinorium.

(3) A low-angle fault exists between the Cambrian Tomstown dolomite and the Ordovician Grove limestone.

(4) This fault, assuming considerable strike extent along the eastern toe of Catoctin Mountain, could explain anomalous stratigraphic relationships in the area. The local absence of Antietam quartzite and Tomstown dolomite could be explained by faulting instead of facies change or one or more unconformities.

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GRAVITY MEASUREMENTS IN THE VIRGIN ISLANDS

By G. LYNN SHURBET, J. LAMAR WORZEL, AND MAURICE EWING

ABSTRACT

Ten new gravity stations on St. Thomas and 21 stations on St. Croix have been established with the Frost geodetic gravimeter. With new submarine gravity stations made in this area with the Vening Meinesz pendulum apparatus, a 200-km profile is formed across the Virgin Islands. Charts are presented showing simple Bouguer anomalies on land and free-air anomalies at sea.

On St. Thomas, contours of the simple Bouguer anomalies are essentially parallel to the strike of the surface structures. On St. Croix, the contours outline the Tertiary sedimentary basin (Cederstrom, 1950). Estimates from the gravity data indicate that these sediments form a wedge which reaches its greatest thickness, about 2 km, near the eastern margin of the basin.

Seismic stations near the gravity profile are used as a guide in computing a structure section across the Virgin Islands. The M-discontinuity is determined by gravity computations to be at about 29 km beneath St. Thomas and St. Croix and 22 km below sea level under the Anegada trough.

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INTRODUCTION

During the submarine cruise on which pendulum-gravity observations were made in the vicinity of the Virgin Islands, the opportunity arose to make 10 gravimeter observations on St. Thomas and 21 on St. Croix. Pendulum observations made in this area during other submarine cruises, which will be reported elsewhere, are included in a gravity profile across the Virgin Islands. These data, with seismic results of others, are the basis of this paper.

ACKNOWLEDGMENTS

The authors are grateful to Hugh Traphagen for making the gravimeter observations as well as many of the observations at sea; to J. Ewing, C. B. Officer, R. J. Edwards, H. R. Johnson, M. Ewing, and G. Sutton for allowing

seismic results to be used prior to their publications; and to Elizabeth Skinner and Annette Trefzer for assistance in computing and drafting.

The sea stations were made possible through the co-operation of the Commander, Submarine Force, Atlantic Fleet, and the officers and crew members of USS DIABLO (SS 479), USS CONGER (SS 477), USS BALAO (SS 285), and USS ARCHERFISH (SS 311).

This work was carried out under Contract N6-onr-271 T.O. 8 with the Office of Naval Research, Department of the Navy.

Station positions and elevations given in Tables 1 and 2 were determined using U. S. Coast and Geodetic Survey charts (3240 and 3242) and an aneroid barometer. Elevations were measured with reference to the observed ocean surface, and by repetition were shown to be accurate to about 25 feet on St. Croix and 50 feet on St. Thomas, corresponding to errors in simple Bouguer gravity anomaly of about 1.5 and 3.0 mgal.

TABLE 1.—SUMMARY OF GRAVITY OBSERVATIONS IN ST. THOMAS

Station number	Date 1954	Latitude North	Longitude West	Elevation Feet	Observed gravity Gals.	Internation. formula gravity	Free-air anomaly Mgals	Bouguer anom. Mgals
95*	16 Feb.	.....	.....	.....	.....	.....	.....	.....
"	"	.....	.....	.....	.....	.....	.....	.....
"	17 Feb.	.....	.....	.....	.....	.....	.....	.....
"	"	.....	.....	.....	.....	.....	.....	.....
"	"	.....	.....	.....	.....	.....	.....	.....
95	21 Feb.	.....	.....	.....	.....	.....	.....	.....
"	"	.....	.....	.....	.....	.....	.....	.....
"	25 Feb.	.....	.....	.....	.....	.....	.....	.....
95†	.....	18–20.13	64–57.29	12	978.6835	978.5588	126	125
96	16 Feb.	18–21.43	64–58.68	942	978.6318	978.5600	160	126
97	16 Feb.	18–21.28	64–57.11	1027	978.6251	978.5599	162	125
98	17 Feb.	18–20.78	64–57.36	322	.6675	.5594	138	127
99	"	18–20.22	64–55.12	12	.6875	.5589	130	129
100	"	18–19.39	64–52.71	20	.6859	.5582	130	129
101	"	18–19.50	64–51.35	5	.6875	.5583	130	130
102	17 Feb.	18–20.22	64–53.45	120	978.6840	978.5589	136	132
103	"	18–21.47	64–53.98	184	.6846	.5600	142	135
104	"	18–21.96	64–55.37	8	.6952	.5605	136	135
105	"	18–21.21	64–55.56	677	.6480	.5598	152	127

* Station #95 established by G. Lynn Shurbet in February 1953 from L. G. O. Base #1. Number of reoccupations shown here to indicate drift control for this survey.

† Adopted value

GRAVIMETER OBSERVATIONS

The Frost geodetic gravimeter used has a range of about 4000 mgal for a single setting of the latitude adjustment; the reading spring is linear over the range used with a scale constant of 2.667 mgal/scale division. A reading is accurate to about ±0.1 scale division, and drift is normally less than the reading errors for periods up to several days.

Observed gravity values were determined relative to station 95. Gravimeter drift is known from station reoccupations (Tables 1 and 2) to have been less than reading error (±0.3 mgal) during the 6-day period of these measurements. Therefore, the observed gravity values are accurate to about 1 milligal relative to the U. S. Coast and Geodetic Survey base in the Department of Commerce Building, Washington, D. C. (980.118 gals). Details of the tie between station 95 and the Washington base are given by Shurbet and Ewing (1956). Comparative pendulum and gravimeter values in St. Thomas harbor are shown in Table 3. The published

TABLE 2.—SUMMARY OF GRAVITY OBSERVATIONS IN ST. CROIX

Station number	Date 1954	Latitude North	Longitude West	Elevation feet	Observed gravity Gals	Internation. formula gravity	Free-air anomaly Mgals	Bouguer anom. Mgals
106	21 Feb.	.....	.....	.....	978.6648	.....	.....	.....
"	"	.....	.....	.....	.6648	.....	.....	.....
106*	.....	17–42.27	64–47.96	65	.6648	978.5254	146	143
107	"	17–43.48	64–47.59	60	.6640	.5264	143	141
108	"	17–43.82	64–46.45	75	.6627	.5267	143	140
109	21 Feb.	17–43.75	64–44.91	90	978.6616	978.5267	143	140
110	"	17–44.29	64–43.19	205	.6739	.5272	166	159
111	"	17–44.49	64–43.22	205	.6742	.5273	166	159
112	"	17–42.81	64–42.72	55	.6824	.5258	162	160
113	"	17–42.80	64–41.16	50	.6864	.5258	165	164
114	21 Feb.	17–43.20	64–39.97	50	978.6872	978.5262	166	164
115	"	17–43.99	64–40.08	90	.6875	.5269	169	166
116	"	17–43.54	64–38.49	130	.6808	.5265	167	162
117	"	17–44.18	64–36.66	12	.6894	.5271	163	163
118	"	17–45.46	64–34.03	225	.6734	.5282	166	158
119	21 Feb.	17–45.39	64–36.07	30	978.6936	978.5282	168	167
120	"	17–45.65	64–37.58	20	.6963	.5284	170	169
121	"	17–45.27	64–39.74	35	.6958	.5280	171	170
122	"	17–44.79	64–41.67	35	.6902	.5276	166	165
123	"	17–45.71	64–44.47	75	.6710	.5284	150	147
124	21 Feb.	17–42.78	64–49.87	125	978.6702	978.5258	156	152
125	"	17–41.94	64–52.59	95	.6696	.5251	153	150
126	"	17–44.46	64–50.91	315	.6643	.5273	167	155

* Adopted value

TABLE 3.—OBSERVED GRAVITY VALUES IN ST. THOMAS HARBOR

Observation	Data	Station number	North latitude	West longitude	Observed gravity-gals
Vening Meinesz	1928	38	18–20.0	64–56.0	978.693
USS BARRACUDA	1937	None	–20.2	–55.2	.685
Frost gravimeter	1954	99	–20.2	–55.1	.688
USS DIABLO	1953	33	–20.1	–57.3	.681
USS DIABLO	1953	28	–20.1	–57.2	.680
Frost gravimeter	1953	95	–20.1	–57.3	.684

value by Vening Meinesz and Wright (1930, p. 56) has been increased by 6 mgal to allow for the change in base stations of the U. S. Coast and Geodetic Survey (Duerksen, 1949, p. 2). The USS BARRACUDA value was observed by Ewing (1937).

Latitude corrections using the International Gravity Formula of 1930, elevation corrections using 0.0941 mgal/ft. as the vertical gravity gradient, and simple Bouguer corrections, assuming a crustal rock density of 2.84 (Worzel and Shurbet, 1955a, p. 91), were applied to the observed gravity values to give the simple Bouguer anomalies listed in Tables 1 and 2. The anomalies are probably accurate to 3 mgal on St. Thomas and 2 mgal on St. Croix.

CORRELATION OF GRAVITY ANOMALIES WITH SURFACE GEOLOGIC FORMATIONS

St. Thomas

Figure 1 shows the gravity-station positions and simple Bouguer anomaly contours on St.

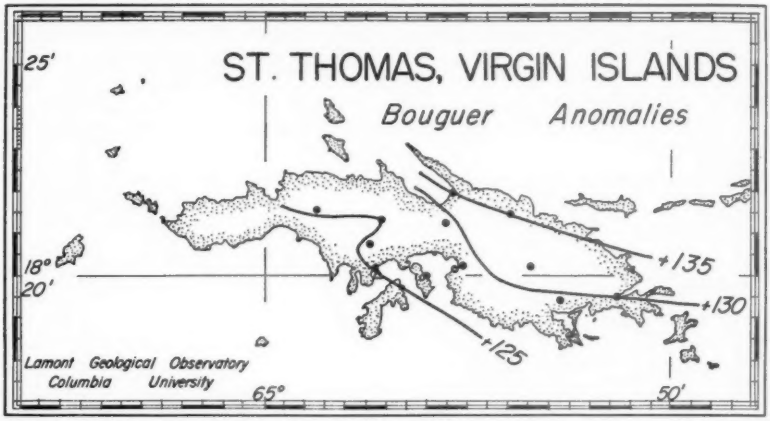

FIGURE 1.—GRAVITY-STATION POSITIONS AND SIMPLE BOUGUER ANOMALY CONTOURS, ST. THOMAS

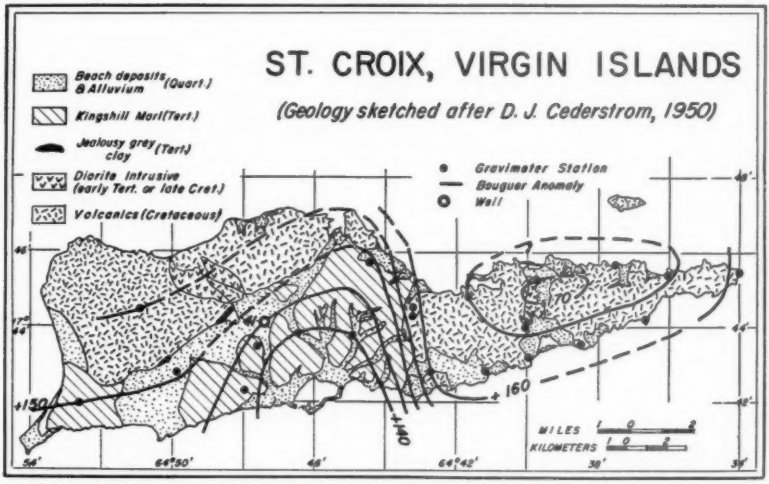

FIGURE 2.—GEOLOGIC MAP OF ST. CROIX WITH SIMPLE BOUGUER ANOMALY CONTOURS

Thomas. The contours, though poorly controlled, may be considered as equally spaced lines trending about N. 65° W., parallel to a number of linear features of the island. The anomaly which departs most from this simple pattern had the greatest elevation (1027 ft).

According to Cleve (1871, *in* Kemp, 1926, p. 20), St. Thomas is composed almost entirely of the "blue beach" formation, a conglomerate or breccia of volcanic origin (Cretaceous) with a thickness of at least 2 km. A strip about half a mile wide along the northeastern coast is composed of stratified metamorphic rocks (clay slate, schists). Cleve's observations have been largely confirmed by Meyerhoff (1926, p. 92, 95) who noted that the structure in eastern St. Thomas strikes N. 65°–70° W. (p. 98). Thus the gravity contours are essentially parallel to the strike, and agree in trend and in absolute value with those found on Puerto Rico (Shurbet and Ewing, 1956) where the contours are roughly parallel to the trend of the platform, increasing from about +100 mgal on the north and south coasts to about +160 mgal along the central east-west axis.

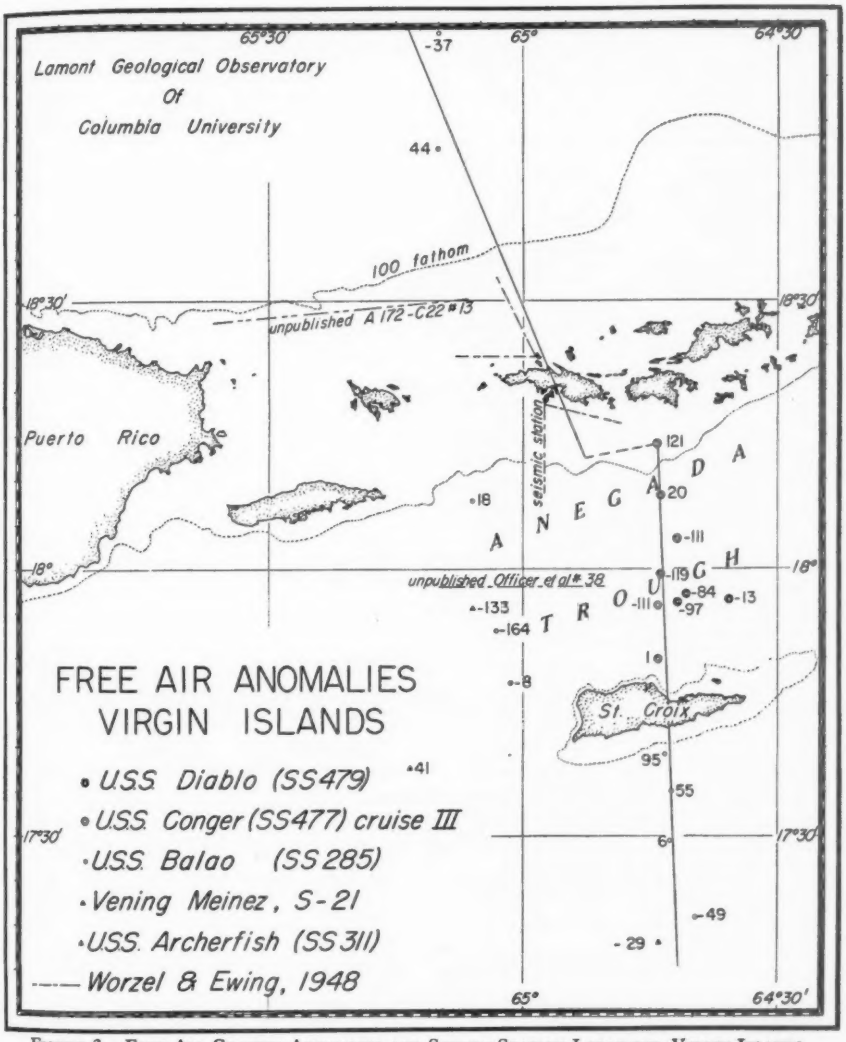

FIGURE 3.—FREE-AIR GRAVITY ANOMALIES AND SEISMIC-STATION LOCATIONS, VIRGIN ISLANDS

St. Croix

Figure 2 shows the gravity-station positions on St. Croix, contours of the simple Bouguer anomalies, and a geologic map sketched after Cederstrom (1950, Pl. 1). Inspection of the anomaly contours indicates a mean anomaly for the area of +150 to +160 mgal, with one minimum at +140 mgal which can result only from a considerable volume of low-density rock. The gravity minimum correlates with the Tertiary sedimentary basin, and gives an indication of the thickness of the sediments. Only minimum thicknesses of these sediments are known. Cederstrom (1950, p. 94) reports over 100 wells on St. Croix, most of which were drilled in the Tertiary basin; however, only one well (41, Fig. 2) is deeper than 500 ft. There a depth of 1508 feet was drilled without reaching

the Cretaceous basement. Alluvium to a depth of 25 feet (p. 28) was penetrated, underlain by 108 feet (p. 21) of Kingshill marl, and the Jealousy formation to a depth of 1,508 feet

The anomaly of +170 mgal over the diorite intrusive near the eastern end of St. Croix may indicate a gravity maximum, but sufficient data are not available to warrant such a conclusion

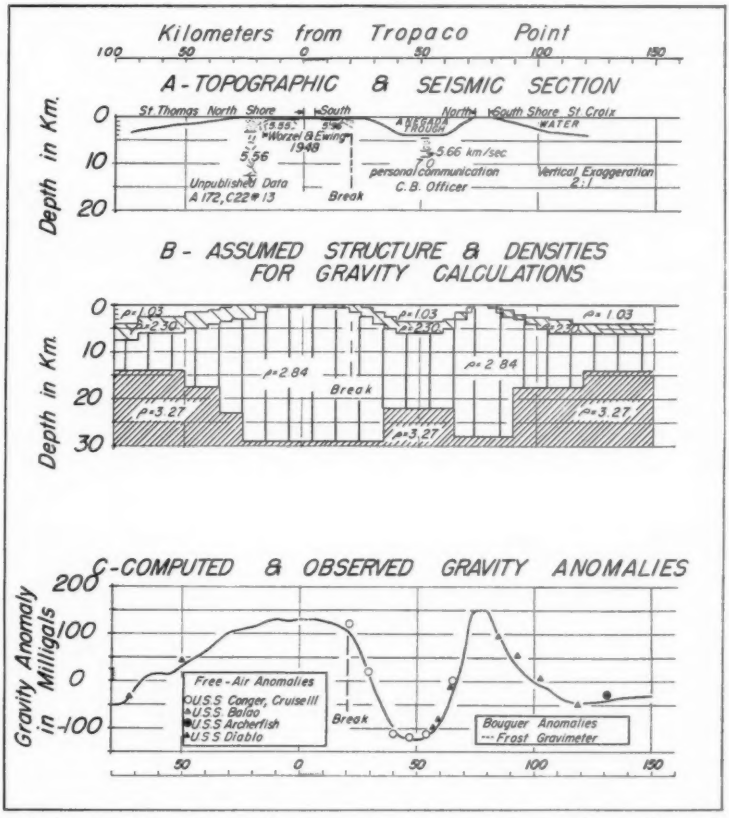

FIGURE 4.—SEISMIC DATA, GRAVITY ANOMALIES, AND STRUCTURE SECTION ACROSS VIRGIN ISLANDS

(p. 94). Other evidence (p. 21) shows that the Kingshill marl increases in thickness from west to east, being a few hundred feet thick near the eastern margin of the basin. The steeper gravity gradient on the eastern side of the basin probably indicates that the thickness of the entire column of sediments also increases from west to east, reaching its maximum thickness near this eastern margin. Assuming a mass deficiency of 0.5 for the sediments relative to the volcanics, the residual anomaly of 20 mgal at the eastern margin indicates a sediment thickness of about 2 km.

or to permit comparison with the diorite area in the western part of the island.

STRUCTURE SECTION ACROSS VIRGIN ISLANDS

Figure 3 shows free-air gravity anomalies at sea stations and seismic-station locations in the vicinity of the Virgin Islands. The seismic results have been used as a guide in computing a structure section along the solid line profile, using free-air anomalies at sea and simple Bouguer anomalies on the islands. All free-air anomalies excepting those about 20 miles west

of the profile have been projected according to sounding to the profile line.

Figure 4A shows the topography along the profile and the projected seismic information. Figure 4B shows densities assumed and the structure section which, when compared to the standard continental (33 km, density 2.84) and oceanic (5 km, density 1.03; 1 km, density 2.30; 4.5 km, density 2.84; 22.5 km, density 3.27) crustal sections of Worzel and Shurbet (1955a, p. 91), give the computed anomaly curve shown by the solid line in Figure 4C. For this computation, the blocks in Figure 4B are considered to be infinite in the direction perpendicular to the drawing. In Figure 4C the triangle and circles indicate observed free-air anomalies; the dashed lines indicate the approximate mean observed Bouguer anomalies over the islands. The agreement of the computed curve with the observed points is considered adequate.

The structural configuration shown in Figure 4B is not subject to much change unless radically different assumptions about density are made. The topographic section is well controlled by sounding information, and the sediment thicknesses are reasonably well determined by seismic stations; therefore, the configuration of the M-discontinuity is determined from the gravity data. The density values used are based on several earlier studies (Worzel and Shurbet, 1955a; 1955b; Shurbet and Ewing, 1956; Ewing and Worzel, 1954, p. 170). As a measure of the change in Figure 4B which might be brought about by different density assumptions, it is noted that an increase in sediment density to 2.50 would lower the M-discontinuity under the Anegada trough by about 2.5 km.

The section of the Virgin Islands platform (Fig. 4B) is almost identical with respect to width and crustal thickness to that of Puerto Rico deduced from a more detailed study (Shurbet and Ewing, 1956). The St. Croix platform has the same thickness within the accuracy attainable by our method of computation for a block of such limited extent. The most striking feature (Fig. 4B), however, is the relatively thin crustal rock section beneath the Anegada trough which provides a clue to the origin of the trough.

In the opinion of most authors who have written about its development this trough is a rift structure, a result of downfaulting of a long, narrow block (Vaughan, 1918, p. 626; 1919, p. 81; Taber, 1922, p. 112; Meyerhoff, 1926, p. 87; 1933, p. 195; Hess, 1933, p. 36).

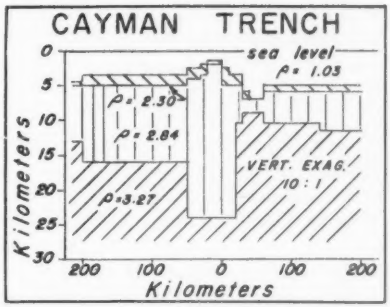

FIGURE 5.—CAYMAN TRENCH SECTION

Taber believed normal faulting occurred on both sides of the trough as a result of tension brought about by the bowing of a broad arch or dome. The central block sank under gravitational forces, being no longer supported after faulting occurred. Myerhoff believed that the block was depressed by compressional forces from the south. Hess believed differential horizontal motion, the Caribbean block moving eastward along a tear fault relative to the block north of it, relieved compression and allowed block faulting. The blocks sank, being no longer supported by the vertical component of the compressive forces. Bucher (1952, p. 83) concurrent with Hess' opinion that differential horizontal motion was responsible for tension fracturing in the trough. However, Bucher's hypothesis of tensional fractures developing diagonally across an east-west shear zone at the northern edge of the Caribbean Sea basin requires much less eastward movement of the Caribbean block relative to the Greater Antilles than does Hess' hypothesis. Eardley (1954, p. 738–742) discussed several objections to both hypotheses, although he prefers the concept of tear-fault origin of the trough (p. 741).

The thin section of crustal rocks under the trough suggests extension of the crust. Extension is further suggested by the crustal similarity between St. Croix and the Puerto Rico-Virgin Islands platform and the difficulty of separate origin of the small silicic block of St. Croix.

A structure section deduced from gravity evidence shows a thin section of crustal rocks

under the Cayman Trench (Fig. 5). Ewing and Heezen (1955, p. 264) concluded that this trench also was produced by extension.

Conclusions

(1) Contours of simple Bouguer anomalies on St. Thomas are essentially parallel to the strike of the surface structure, and agree in trend and in absolute value with those found on Puerto Rico.

(2) One gravity minimum of about 20 mgal on St. Croix can be correlated with the Tertiary sedimentary basin. The maximum depth of the basin, near its eastern margin, is estimated to be 2 km.

(3) The Puerto Rico platform and the Virgin Bank have the same thickness of crustal rocks (29 km), and are similar in many other respects. The St. Croix platform is also about 29 km thick, but it is separated from the Virgin Bank by a 30-km-wide strip of crustal rocks only 16 km thick. This thin section is believed to have been produced by extension of the crustal rocks.

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Texas Technological College, Lubbock, Texas; Lamont Geological Observatory (Columbia University), Palisades, N. Y.; Lamont Geological Observatory (Columbia University), Palisades, N Y.

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CARBONATITES: A REVIEW

By W. T. PECORA

ABSTRACT

The carbonatites are essentially carbonate-silicate rock with a great variety of other minerals. In this review the writer stresses the field and geochemical relationships of the carbonatites and alkalic igneous rocks and concludes that carbonatites were deposited by carbonatic solutions having a wide range of temperature, pressure, and concentration and derived from alkalic magmas during the process of silicate crystallization. Brogger's concept of carbonate magma is evaluated in the light of more recent field and laboratory investigations, and the conclusion is reached that a carbonate magma in the normal sense is less likely to exist than carbonate-rich solutions which at elevated temperature and pressure can have a higher concentration of dissolved ingredients than normally believed for hydrothermal solutions.

At many localities the carbonatites occur as veinlike or dikelike bodies or as cores in volcanic plugs of alkalic rocks. Recent investigations indicate that the carbonatites and related alkalic rocks represent a relatively unevaluated category of ore deposits that contain an impressive reserve of such rare commodities as niobium (columbium), titanium, zirconium, rare earths, barium, strontium, uranium, magnetite, phosphate, vermiculite, and agricultural lime.

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Introduction

General Statement

Those carbonate-rich rocks that petrologists call "carbonatites" currently are providing a focus of great interest because of their potential economic importance. More than 30 occurrences are now recorded in the literature, and at the surprising rate of new discoveries over the past decade many more will be found in the next decade. Moreover, several of those occurrences known for more than 50 years are being re-examined in more detail. The activity in this research area has increased so markedly since World War II, and the new papers describing them are so widely distributed in the geologic literature, that a summary paper describing their general features is timely. The carbonatites are somehow related to the alkalic rocks with which they are universally associated on several continents. Their origin has been in dispute for many years. This review defines the problem more sharply by treatment of the worldwide occurrences as a class.

Partial reviews of carbonatite localities have appeared in the past few years (Olson and others, 1954, p. 70–72; Schröcke, 1955; Deans, 1955; Lombard, 1955). Reports on a few occurrences referred to in the present review are in progress and may be published even before this review. The published information available before 1956 and the writer's personal acquaintance with the four carbonatite occurrences in the United States form the background of the present paper.

The economic potential of carbonatites and related alkalic complexes as new sources of raw materials is impressive. Efforts expended in many countries have already established a substantial reserve in this class of rocks of such commodities as the rare earths, barite, niobium (columbium), uranium, phosphate, and agricultural lime.

Nomenclature

In his classic memoir on the Fen area in Norway Brögger (1921, p. x, xi, 350, 356) used the term "Karbonatite", in the plural sense only, to embrace a family of carbonate-rich and silicate-carbonate rocks to which he assigned specific rock names such as sövite, rauhaugite, etc. He clearly stated his belief in their igneous origin by crystallization from a carbonatic magma derived from an alkalic, subcilicic magma that had become enriched in CO_2 by assimilation of sedimentary limestone. Since that time, however, other hypotheses have been offered to explain their mode of formation, but the term carbonatite has been retained for those carbonate-rich rocks that might have originated from a hot carbonatic fluid genetically derived through some magmatic process.

For this reason other meanings of the term should be avoided. Kay (1951, p. 5), for example, has used carbonatite to embrace carbonate rocks of sedimentary origin in geosynclines. Because of the wealth of earlier usages in the petrologist's sense, the writer considers Kay's usage inappropriate. In some metamorphic terrains, carbonate rock that has undergone plastic deformation in adjustment to regional stresses so that it appears intrusive into other rocks, older or younger, might also be excluded from the carbonatite family. This applies particularly to situations like that of the Grenville formation in the Adirondacks of New York (Buddington, 1939, p. 11–17). Carbonate rocks that exhibit contact metamorphism and more commonly referred to as "skarns" are also excluded, as at Scawt Hill, Ireland (Tilley, 1931, p. 439, 468). Skarn rocks in contact with alkalic igneous rocks and xenoliths in igneous rocks are also excluded, as discussed in a later section of this paper.

The writer thinks it better to retain the term somewhat within the sense imposed by Brögger. It is clearly implied in the petrologic literature that the carbonatites are a special kind of carbonate-rich rock genetically related to the alkalic rock-forming process and alkalic-magma irruption. The carbonatic fluid, whatever its temperature, concentration, or physical state, is an active, invading agent capable of precipitating minerals.

Problem Defined

The principal mystery of the carbonatites lies in the dual problem of their mode of formation and of the ultimate source of their carbon dioxide and rare constituents. For one or another field occurrence, various authors have

interpreted the carbonate rock as igneous, hydrothermal, or xenolithic and the carbon dioxide as juvenile or recycled. The problem of the origin of carbonatites cannot be divorced from that of the origin of alkalic igneous rocks, for the geochemical concentration of certain elements in both classes of rock, their close spatial and temporal association, and their chronological position late in provincial orogenies join them in any genetic consideration. Although some alkalic rock masses do not contain carbonatites, all the carbonatites described in the literature occur within alkalic petrographic provinces. The absence of carbonatites from some alkalic complexes, nevertheless, led Adamson (1944) to adopt the hypothesis of two chemically different alkalic magma stems.

Acknowledgments

A great number of individuals freely discussed the problem of carbonatites with the writer, offered critical comments, and suggested pertinent references. Among them the following deserve special mention: Dr. F. Dixey of the British Colonial Survey, Professor C. E. Tilley of Cambridge University, Professor E. N. Cameron of the University of Wisconsin, and Messrs. Michael Fleischer, Earl Ingerson, K. J. Murata, and E. P. Kaiser of the U. S. Geological Survey. Communications from interested readers are welcomed and encouraged, for the carbonatites are truly a "hot" subject!

Geologic Relations

Distribution

A provisional list of world-wide occurrences of carbonatites is given in Table 1. Although incomplete, the 32 localities include all those occurrences described as carbonatites before 1956. Additions could be made to the list if more liberty were taken by the reviewer in evaluation of other rock occurrences known to be or suspected of being carbonatites. Future literature will probably include other localities in the Tertiary provinces of Africa, Europe, and Asia; in the early Mesozoic province of southeastern Brazil; in the Monterigian province of eastern Canada; and in many other regions where alkalic rocks occur.

Excluded from the list are a number of localities where the carbonate rocks in association with alkalic rocks are described or interpreted as skarns or xenoliths. As discussed in a later section of this review, a few of the so-called xenoliths are now classed as carbonatites after re-examination (Magnet Cove, Loolekop, and Kaiserstuhl).

Excluded also are a great number of deposits described as carbonate veins. Perhaps some of them might be included as carbonatites, particularly as they occur in alkalic rocks and especially if the term carbonatite is eventually adopted for all carbonate-rich veinlike deposits. Some of these localities are described by: Barth (1927) on Seiland; Callisen (1943) near Ivigtut; Dorfman and Timofeev (1939) in Turkestan; Kranck (1928) on the Turja Peninsula (Kola); Kuzmenko (1940) near Mariupol; and Smorchkov (1939) in Turkestan. All these localities are characterized by feldspathoidal igneous rocks. The veins are perhaps as justifiably to be considered carbonatites as other veinlike occurrences listed in Table 1. There is enough difference in mineral composition, however, to lead the reviewer to leave them off the list provisionally.

General Field Relations

Carbonatites occur almost exclusively in stocks or plugs of alkalic igneous rocks as one or more regularly or irregularly shaped bodies. Rarely they occur also as dikelike bodies in the near-by country rock. The size and shape of the areas underlain by carbonatites and of the alkalic rock complexes in which they occur are indicated, where information is known, in Table 1. The alkalic igneous complexes, generally oval or circular, encompass areas of from 1 to 20 square miles. Except for the alkalic district in the Kola Peninsula, all the subsilicic, alkalic rock complexes throughout the world seem to be oval or circular and but a few square miles in area—in contrast to the much larger igneous rock complexes of granitic or gabbroic composition. The area of the carbonatites bears no direct relation to the size of the stock or plug in which they occur. The largest carbonatites are 2–3 square miles in area and are exposed in vertical relief for several hundred feet. For some of them, therefore, the volume is considerable.

Within some complexes the carbonatites form a "core", but in many they are present as several mappable units. Larsen (1942, Pl. 1), for example, mapped a single large area and a great number of dikes of carbonate rock in the Iron Hill stock in Colorado. At a few localities, as in the Bearpaw Mountains, the carbonate-silicate rocks occur only within the stock complex and only as veinlike bodies. At others, as at Magnet Heights (Strauss and Truter, 1951b) and Chishanya (Swift, 1952), dikelike bodies occur in the country rock beyond the border of the complex. In plan some of the dikelike bodies of carbonatites are curved and are inclined in attitude. This structural relationship led Von Eckermann (1948, p. 85) to infer the existence of intersecting carbonatite cone sheets having different depths of foci. For several East Africa localities, "ring and core" (Mennell, 1946), "collar structure" (Williams, 1952), and "cone sheet" (Davies, 1947; Saggerson, 1952) describe the form of the carbonatite bodies. At some localities, as at Homa Mountain (Saggerson, 1952), carbonatites occur in several subordinate volcanic necks in addition to the principal vent, and in several places lower on the slope area of the cone.

Authors have used the terms carbonatite dikes or veins presumably with a conscious prejudgment as to mode of formation. Among American geologists the two terms are sharply distinguished on a genetic basis—perhaps too rigidly. A "dike" has come to mean a tabular body crystallized from a magma in which the volume of original fluid is essentially equivalent to the volume of the solid matter now observed; "vein" on the other hand has come to mean a tabular body whose minerals have precipitated from a dilute aqueous or volatile solution, and the volume of the original solution is many many times more than the volume of the solid matter now observed. It is unfortunate that we have not retained in English, as has been done in some other languages, a single term to connote form without genesis. The terms dikelike, veinlike, vein-dike attempt to skirt the genetic connotation particularly with reference to such rocks as carbonatites, which are composed of minerals some of which are normally typical of dikes and some of veins.

It might be an excellent idea to use the term carbonatite without the genetic connotation of magma implied by Brögger and to extend it to include all those carbonate-rich deposits formed from hot fluids. This is the position being taken by the reviewer in a paper, now in preparation, describing the silicate-carbonate-sulfide deposits in the Bearpaw Mountains, Montana (Pecora, 1956).

Many writers call attention to a fabric in some carbonatites which they describe as "streaming", "foliation", "flow structure", and "fluxion structure". For the Sulphide Queen deposit at Mountain Pass, Shaw (Olson *et al.*, 1954, p. 48, Pl. 6) has mapped this feature in great detail. Garson (1955, p. 314–317) illustrates the feature in his preliminary paper on the Chilwa Island carbonatite. The same feature has been mentioned for many of the cores and dikelike bodies at other localities. Most European authors consider this fabric to be the result of magmatic flow. It should be noted, however, that this fabric could be due to plastic readjustment of solid carbonate rock after its emplacement or deposition. The point is emphasized here only because the feature has been cited as proof of magmatic flow banding.

Petrographic Relations

The silicate rocks occurring with the carbonatites in the alkalic complexes show such a wide variety of texture and mineral assemblage that a list of the assigned rock names is indeed formidable (Table 1). The rocks portray many combinations of mafic and felsic essential minerals to yield a sequence of dark to light varieties in several general petrographic groups. Augite, olivine, and biotite are the principal mafic minerals. Potassium feldspar and nepheline are the most abundant felsic minerals. Chemically the rocks are characterized by a deficiency in silica with respect to alkalis and alumina. The potassium feldspar is commonly microperthitic, the nepheline potassic, and the augite diopsidic and aegiritic. Some of the rocks rich in mafic minerals have been called mica periodotite and mica pyroxenite, but these are "alkalic" in contrast to peridotite and pyroxenite occurring in other provinces associated with gabbro and anorthosite. Quartz is very rare in the suite but has been recorded in the "mixed" rocks at the border of some of the complexes. The terms "fenite" and "fenitization"

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	Name	Location	Principal references	
1	Fen	Norway: in the Telemark district, near Oslo	Brögger (1921); Bowen (1924); Brauns (1936); Tomkeiff (1938); Barth (1944); Björlykke (1955)	Carbonate rock constitute by massive calcitic roc rock (rauhaugite), and as ringite (with aegiri pyroxene)
2	Alnö	Sweden: about 10 km NE. of Sundsvall, on Alnö and near-by islands in Klingerfjarden Bay	Holmquist (1896); Hogbom (1895; 1909); Von-Eckermann (1948; 1950; 1952)	Massive and dikelike occ less than 5 per cent of in bay area
3	Kaiserstuhl	Germany: in the Rhine Valley, near Schelingen, in Breisgau	Knop (1892, p. 314); Graeff (1893, p. 471–485); Metschke (1938); Schneiderhohn (1948); Leibrandt (1948); Eigenfeld (1948)	Quarries expose substan tephrite and tephrite b
4	Magnet Cove	United States: at Magnet Cove, 12 miles east of Hot Springs, Arkansas	Williams (1890); Washington (1900); Ross (1941, p. 24); Fryklund and Holbrook (1950); Fryklund *et al.* (1954)	Kimsey Quarry exposes feet of coarsely crystalli syenite altered to vesuv rock with same compos irregular framework i weathered
5	Iron Hill	United States: near Powderhorn P.O., 20 miles SW. of Gunnison, Colorado	Larsen (1942)	Principal mass at Iron H rocks of stock; about 2 feet
6	Mountain Pass	United States: at Mountain Pass, 35 miles NE. of Baker, California	Olson *et al.* (1954); Jaffe *et al.* (1953); Jaffe (1955)	Large mass of carbonate shonkinite mass 2400 bastnaesite and 20–30 in district; calcite exce
7	Rocky Boy	United States: head of Big Sandy Creek, Bearpaw Mountains, Montana	Pecora (1942; 1956); Pecora and Kerr (1953)	Several veinlike bodies o tassium feldspar, bioti matitic syenite dikelik calcite-feldspar rock
8	Lokupoi	Uganda: at the site of Napak volcano in the Elgon Chain in Karamojo	Bisset (1935); King (1949)	Central mass in volcanic above plains and cons streaking of rock inclus
9	Toror	Uganda: at the site of Toror volcano in the Elgon Chain in Karamojo	Bisset (1935)	Central mass in volcanic
10	Tororo Hills	Uganda: near Tororo station in the Eastern Province	Davies (1947; 1954); Davies and Bisset (1947); Williams (1952)	Central mass in alkalic and 1½ miles long
11	Bukusu	Uganda: NE. of Tororo station in the Eastern Province	Davies (1947); Taylor (1955)	Two separate masses in by tuff, and rises 400 fe rock beyond border of
12	Sukulu	Uganda: S. of Tororo station in the Eastern Province	Davies (1947; 1954); Williams (1950); Sinclair (1955)	Central circular area of c complex between carbo
13	Sekululo	Uganda: NE. of Tororo station in the Eastern Province	Davies (1947)	Carbonate rock almost co volcanic deposits; alk scattered exposures of
14	Rangwe	Kenya: on Kisingiri Mountain, in the Kavirondo Gulf area west of Homa Bay	Pulfrey (1949); Shackleton (1951)	Central mass of carbona vertical relief of 800 fe
15	Ruri	Kenya: on Ruri Mountain, in the Kavirondo Gulf area west of Homa Bay	Pulfrey (1949); Shackleton (1951)	Central mass of carbonate in detail
16	Homa	Kenya: on Homa Mountain, in the Kavirondo Gulf area east of Homa Bay	Pulfrey (1949); Shackleton (1951); Saggerson (1952)	Several areas on Homa M and mixed volcanic br 1½ miles in diameter. Mountain, some at lak
17	Mrima	Kenya: at Mrima Hill, 5 miles SE. of Jombo, near Indian Ocean	Baker (1953)	Veinlike carbonate mass laterite and probably alkalic complex
18	Mbeya	Tanganyika: at Panda Hill, 13 miles SW. of Mbeya between Lakes Rukwa and Nyasa	Fawley and James (1955)	Massive and dikelike calc exposed in vertical relie tains carbonate
19	Chilwa Island	Nyasaland: on Chilwa Island in Lake Chilwa	Dixey *et al.* (1935, p. 10); Smith (1953); Garson (1955)	Central area of crystallin about 1400 feet above Streaking and flow stru
20	Tundulu	Nyasaland: near the south shore of Lake Chilwa	Dixey *et al.* (1935, p. 12); Garson (1955)	Several separate masses canic vent principally
21	Songwe	Nyasaland: between Lake Chilwa and the Mlanje Hills	Dixey *et al.* (1935, p. 12)	by ½ mile with vertica Carbonate rock near wes area with vertical relie
22	Kangankunde	Nyasaland: about 50 miles west of Lake Chilwa	Dixey *et al.* (1935)	agglomerate make up Three separate carbonat
23	Muambe	Mozambique: about 14 miles NE. of the Lupata Gorge of the Zambesi River	Dixey *et al.* (1935, p. 9)	associated with breccia in gneiss beyond borde Central area of carbonat in diameter with vertic bordered by ring of alk
24	Nkumbwa	Northern Rhodesia: at Nkumbwa Hill, 15 miles E. of Isoka	Reeve and Deans (1954); Deans and McConnell (1955)	Carbonate rock forms pri
25	Shawa	Southern Rhodesia: in the upper Sabi Valley near Shawa	Mennell (1946)	1000 feet and area abo Central mass of carbona
26	Dorowa	Southern Rhodesia: in the upper Sabi Valley near Dorowa	Mennell (1946)	alkalic rocks Central mass of carbonat
27	Chishanya	Southern Rhodesia: at Chishanya Hill in the Sabi Valley	Swift (1952)	rocks; other masses of Central mass of carbonat
28	Loolekop	South Africa: in the Palabora district of NE. Transvaal	Russell *et al.* (1954); Shand (1931); Du Toit (1931); Schwellnus (1938); Gevers (1949)	alkalic rocks. Smaller m of complex Principal mass of carbon feet forms central core
29	Spitzkop	South Africa: in the Sekukuniland district of eastern Transvaal	Strauss and Truter (1951a); Shand (1921)	carbonate in other rock Central mass of carbonat
30	Magnet Heights	South Africa: in the Sekukuniland district, 14 miles from Spitzkop, eastern Transvaal	Strauss and Truter (1951b)	with relief of about 300 beyond border of comp Veinlike carbonate body
31	Premier	South Africa: in the Premier mine, Transvaal	Daly (1925)	eral kinds of igneous ro Several lenticular and di breccia pipe, largest of
32	Jacupiranga	Brazil: in the state of São Paulo	Derby (1891, p. 314–315; 1887); Melcher (1954)	Ridgelike area of carbon bordered by alkalic roc

TABLE 1.—GENERAL INFORMATION ON CARBONATITES AND ASSOCIATED ALKALIC IGNEOUS COMPLEXES

Nature of carbonatite occurence	Special features	Area of alk
stitutes about 50 per cent of alkalic complex and represented ic rock (sovite), calcitic dikes (alvikite), massive dolomitic), and iron-rich rock (rodberg), carbonate-silicate rocks such aegirite and feldspar), and kaesinite (with nepheline and	Local concentrations of pyrochlore, niobian perovskite, magnetite, and apatite. Economic investigations in progress; current production 15 tons per month of niobium concentrates	4 square miles
ke occurrences similar to Fen area; exposed carbonate rocks ent of alkalic complex; principal mass conceivably offshore	Local concentrations of pyrochlore, niobian perovskite, apatite, magnetite, fluorite, and barite. Economic investigations during and following World War II	About 20 sq km if cont bay
bstantial mass of carbonate rock locally in contact with rite breccia	Local concentrations of pyrochlore, and niobian perovskite; sampling program indicates reserve of several thousand tons of carbonate rock containing not less than 0.2 per cent Nb_2O_5	Not known in detail
poses part of centrally located, elongate mass 4000 by 500 ystalline carbonate rock that contains inclusions of nepheline vesuvianite-diopside rock; other dikelike masses of carbonate mposition; veinlike bodies in the "Rutile Deposit" occur as ork in fractured and altered older rocks. Area is deeply	Local concentrations of apatite, monticellite, niobian perovskite, and magnetite in the Kimsey deposit and substantial reserve of niobian rutile in the rutile deposit	About 6 square miles
Iron Hill is dolomitic; other dikelike bodies in older alkalic out 2 square miles in area, with vertical relief of about 1000	Dolomite exceeds calcite and ankerite in the carbonate rock; apatite is the principal accessory; local concentrations of calcite-martite (after magnetite) veins in the Iron Hill mass; sulfides rare. Some rare-earth minerals recently identified by members of the U.S. Geological Survey	About 12 square miles
onate rock (Sulphide Queen) adjoining southern border of 2400 by 400 feet and contains (average) 10–15 per cent 0–30 per cent barite; more than 200 barite-carbonate veins e exceeds dolomite in district	Carbonate-barite-bastnaesite rock represents major ore deposit for rare earths and barite; Sulfide Queen deposit contains excess of 25 million tons of rock with 5–10 per cent rare-earth oxide and 20–25 per cent of barite. Rarity of apatite, magnetite, and niobium minerals; local concentrations of galena, pyrite, and monazite; type locality for sahamalite	Nearest is ½ square mi
dies of carbonate rock composed essentially of calcite, po- biotite, and sulfides; largest vein is 18 inches thick; peg- ikelike bodies up to 40 feet thick have well-defined cores of ock	Exceptional concentrations of rare-earth carbonates in some veins; rarity of apatite, magnetite, and niobium minerals; barite crystals in veins and cavities; principal sulfides are pyrrhotite, pyrite, and galena; calcite is strontian; type locality for burbankite and calkinsite	12 square miles
canic plug essentially of carbonate rock rises about 1000 feet constitutes about 15 per cent of plug area; well-defined inclusions in carbonate core	Carbonate rock largely calcite; mineralogy not studied in detail	About 3 square miles
canic plug noted but not described in detail	Features not described	Not known; probably le
lkalic complex rising 700 feet above plains, pear-shaped, g	Intensive exploration for agricultural lime and phosphate; 640 samples of carbonate rock average 1.7 per cent P_2O_5, 80 per cent $CaCO_3$, and 1 per cent MgO. Residual enrichment in lateritic mantle of niobium mineral concentrate	2 square miles
es in alkalic complex; larger is oval-shaped, partly covered 400 feet above plains. Two dikes of carbonate rock in country er of complex	Ring-shaped band of apatite-magnetite-phlogopite-calcite rock investigated as source of phosphate; niobium minerals concentrated by weathering	20 square miles (?), larg
a of carbonate rock about 2½ miles across. Most of alkalic carbonate rock and fenitized country rock concealed	Intensive exploration for agricultural lime and phosphate; 961 samples of carbonate rock average 3.68 per cent P_2O_5, plus 80 per cent $CaCO_3$, and 3.5 per cent MgO	Circular area 3 miles in
ost completely overlain by younger tuff related to the Elgon ; alkalic complex concealed but inferred by presence of es of fenitized granite	Selected samples of weathered carbonate rock contain more than 20 per cent P_2O_5	Circular area 3 miles in
rbonate rock in the Kisingiri volcanic plug with exposed 00 feet	Mineralogy not described in detail	Circular area about 3 mi
onate rock in the Ruri volcanic plug noted but not described	Mineralogy not described in detail	Circular plug about 3 mi
ma Mountain of massive calcitic rock, dikes and cone sheets, ic breccia. Largest mass in the Homa principal vent area neter. Many others in subsidiary vents on slope of Homa t lake level	Calcitic dikes dip 30°–65° and interpreted to be cone sheets; sovite commonly contains biotite, but some varieties are rich in pyroxene; apatite, melanite, magnetite, and sphene common accessory minerals	Principal vent about 3 eral smaller subsidiary
mass on northern slope of Mrima Hill largely concealed by ably related to agglomerate vent subsidiary to the Jombo	Lateritic material presumably derived from carbonate rock rich in iron, manganese, and barite. Intensive exploration in progress	Jombo complex 2 by 1½
e calcitic and dolomitic rock within neck of extinct volcano l relief of 500 feet. Much of vent rock is brecciated and con-	Intensive exploration by drilling has proved several million tons of pyrochlore-bearing carbonate rock averaging about 0.3 per cent Nb_2O_5	Vent complex about 400
talline carbonate rock about 1 mile in diameter and rising bove lake level bordered by agglomerate of volcanic plug. v structure well exposed	Calcite is dominant over dolomite; flow structure conspicuous; lateritic material rich in iron and manganese; study by Garson in progress	Oval vent 2 by 1½ mile
sses of carbonate rock in central area and near rim of vol- ally associated with agglomerate; largest carbonate mass 1 ertical relief of 700 feet	Mineralogy not described in detail	Oval vent 1½ by 1 mile
r western rim of the Mauze volcanic vent about ½ mile in l relief of about 700 feet. Carbonate, brecciated rock, and e up what is locally called the Songwe vent	Mineralogy not described in detail	Mauze complex oval sha
onate rock areas, each about 500–1000 feet in diameter, recciated and agglomeratic vent rock; three additional areas border of plug	Mineralogy not described in detail	Oval vent ¾ by ⅜ mile
onate rock and associated agglomerate rock about 3 miles vertical relief of about 200 feet. Carbonate area forms core of alkalic rocks	Mineralogy not described in detail; local enrichment in iron and manganese by weathering	Circular, about 4 miles i
s principal area of volcanic plug, has vertical relief of about about 1 square mile	Carbonate principally ankeritic dolomite (rauhaugite); pyrochlore and monazite reported in rock; type locality for isokite, new fluophosphate mineral	Oval area 1 by ½ mile
bonate rock about 2 miles in diameter in circular plug of	Abundance of apatite and magnetite recorded	Circular area 4 miles in
onate rock about 500 yards in diameter bordered by alkalic es of carbonate rock in country rock beyond border of plug	Magnetite locally abundant in masses up to 40 feet across	Oval area 2 by 1 miles
onate rock with vertical relief of about 500 feet bordered by ller masses of carbonate rock in country rock beyond border	Local concentrations of magnetite and apatite recorded	About 2 square miles
rbonate rock about 4000 feet long with relief of about 300 core of multiple-zoned alkalic complex. Veinlike masses of rocks	Local abundance of apatite and magnetite recorded; phlogopite locally mined for vermiculite	Palabora complex oval a
bonate rock roughly circular and about 1 mile in diameter t 300 feet. Dikelike masses of carbonate occur in other rocks complex	Both calcite and dolomite reported; apatite and magnetite locally abundant	Oval area 3 by 2 miles
body up to 1 foot wide and 1100 yards long traverses sev- us rocks	Banded character of vein noted; pyrrhotite is principal sulfide mineral	Dike complex
nd dikelike bodies of calcitic carbonate in the Kimberly st of which is about 60 feet thick	Calcite is principal carbonate mineral, but dolomite and ankerite also present; accessory minerals include apatite, magnetite, sphene, and serpentinized olivine	Oval pipe about ½ mile
rbonate rock up to 800 meters long and 300 meters wide c rocks	Apatite, magnetite, and biotite locally abundant; pyrochlore identified in rock	Oval area about 20 squar

TABLE 1.—GENERAL INFORMATION ON CARBONATITES AND ASSOCIATED ALKALIC IGNEOUS COMPLEXES

arbonatite occurence	Special features	Area of alkalic c
) per cent of alkalic complex and represented , calcitic dikes (alvikite), massive dolomitic ock (rodberg), carbonate-silicate rocks such dspar), and kaesinite (with nepheline and	Local concentrations of pyrochlore, niobian perovskite, magnetite, and apatite. Economic investigations in progress; current production 15 tons per month of niobium concentrates	4 square miles
imilar to Fen area; exposed carbonate rocks mplex; principal mass conceivably offshore	Local concentrations of pyrochlore, niobian perovskite, apatite, magnetite, fluorite, and barite. Economic investigations during and following World War II	About 20 sq km if contacts bay
of carbonate rock locally in contact with	Local concentrations of pyrochlore, and niobian perovskite; sampling program indicates reserve of several thousand tons of carbonate rock containing not less than 0.2 per cent Nb_2O_5	Not known in detail
ntrally located, elongate mass 4000 by 500 ate rock that contains inclusions of nepheline oside rock; other dikelike masses of carbonate like bodies in the "Rutile Deposit" occur as d and altered older rocks. Area is deeply	Local concentrations of apatite, monticellite, niobian perovskite, and magnetite in the Kimsey deposit and substantial reserve of niobian rutile in the rutile deposit	About 6 square miles
mitic; other dikelike bodies in older alkalic les in area, with vertical relief of about 1000	Dolomite exceeds calcite and ankerite in the carbonate rock; apatite is the principal accessory; local concentrations of calcite-martite (after magnetite) veins in the Iron Hill mass; sulfides rare. Some rare-earth minerals recently identified by members of the U.S. Geological Survey	About 12 square miles
lphide Queen) adjoining southern border of et and contains (average) 10–15 per cent arite; more than 200 barite-carbonate veins te in district	Carbonate-barite-bastnaesite rock represents major ore deposit for rare earths and barite; Sulfide Queen deposit contains excess of 25 million tons of rock with 5–10 per cent rare-earth oxide and 20–25 per cent of barite. Rarity of apatite, magnetite, and niobium minerals; local concentrations of galena, pyrite, and monazite; type locality for sahamalite	Nearest is ½ square mile
te rock composed essentially of calcite, po- lfides; largest vein is 18 inches thick; peg- to 40 feet thick have well-defined cores of	Exceptional concentrations of rare-earth carbonates in some veins; rarity of apatite, magnetite, and niobium minerals; barite crystals in veins and cavities; principal sulfides are pyrrhotite, pyrite, and galena; calcite is strontian; type locality for burbankite and calkinsite	12 square miles
tially of carbonate rock rises about 1000 feet out 15 per cent of plug area; well-defined rbonate core	Carbonate rock largely calcite; mineralogy not studied in detail	About 3 square miles
d but not described in detail	Features not described	Not known; probably less th
rising 700 feet above plains, pear-shaped,	Intensive exploration for agricultural lime and phosphate; 640 samples of carbonate rock average 1.7 per cent P_2O_5, 80 per cent $CaCO_3$, and 1 per cent MgO. Residual enrichment in lateritic mantle of niobium mineral concentrate	2 square miles
nplex; larger is oval-shaped, partly covered lains. Two dikes of carbonate rock in country	Ring-shaped band of apatite-magnetite-phlogopite-calcite rock investigated as source of phosphate; niobium minerals concentrated by weathering	20 square miles (?), largest i
rock about 2½ miles across. Most of alkalic and fenitized country rock concealed	Intensive exploration for agricultural lime and phosphate; 961 samples of carbonate rock average 3.68 per cent P_2O_5, plus 80 per cent $CaCO_3$, and 3.5 per cent MgO	Circular area 3 miles in diam
overlain by younger tuff related to the Elgon lex concealed but inferred by presence of ranite	Selected samples of weathered carbonate rock contain more than 20 per cent P_2O_5	Circular area 3 miles in diam
n the Kisingiri volcanic plug with exposed	Mineralogy not described in detail	Circular area about 3 miles i
he Ruri volcanic plug noted but not described	Mineralogy not described in detail	Circular plug about 3 miles i
f massive calcitic rock, dikes and cone sheets, gest mass in the Homa principal vent area thers in subsidiary vents on slope of Homa	Calcitic dikes dip 30°–65° and interpreted to be cone sheets; sovite commonly contains biotite, but some varieties are rich in pyroxene; apatite, melanite, magnetite, and sphene common accessory minerals	Principal vent about 3 mile eral smaller subsidiary ven
rn slope of Mrima Hill largely concealed by agglomerate vent subsidiary to the Jombo	Lateritic material presumably derived from carbonate rock rich in iron, manganese, and barite. Intensive exploration in progress	Jombo complex 2 by 1½ mil
olomitic rock within neck of extinct volcano et. Much of vent rock is brecciated and con-	Intensive exploration by drilling has proved several million tons of pyrochlore-bearing carbonate rock averaging about 0.3 per cent Nb_2O_5	Vent complex about 4000 fee
te rock about 1 mile in diameter and rising l bordered by agglomerate of volcanic plug. l exposed	Calcite is dominant over dolomite; flow structure conspicuous; lateritic material rich in iron and manganese; study by Garson in progress	Oval vent 2 by 1½ miles
te rock in central area and near rim of vol- with agglomerate; largest carbonate mass 1 700 feet	Mineralogy not described in detail	Oval vent 1½ by 1 miles
of the Mauze volcanic vent about ¼ mile in t 700 feet. Carbonate, brecciated rock, and cally called the Songwe vent	Mineralogy not described in detail	Mauze complex oval shaped
eas, each about 500–1000 feet in diameter, gglomeratic vent rock; three additional areas	Mineralogy not described in detail	Oval vent ¾ by ⅜ mile
d associated agglomerate rock about 3 miles f about 200 feet. Carbonate area forms core	Mineralogy not described in detail; local enrichment in iron and manganese by weathering	Circular, about 4 miles in dia
a of volcanic plug, has vertical relief of about re mile	Carbonate principally ankeritic dolomite (rauhaugite); pyrochlore and monazite reported in rock; type locality for isokite, new fluophosphate mineral	Oval area 1 by ½ mile
bout 2 miles in diameter in circular plug of	Abundance of apatite and magnetite recorded	Circular area 4 miles in diam
ut 500 yards in diameter bordered by alkalic e rock in country rock beyond border of plug h vertical relief of about 500 feet bordered by carbonate rock in country rock beyond border	Magnetite locally abundant in masses up to 40 feet across	Oval area 2 by 1 miles
	Local concentrations of magnetite and apatite recorded	About 2 square miles
bout 4000 feet long with relief of about 300 ple-zoned alkalic complex. Veinlike masses of	Local abundance of apatite and magnetite recorded; phlogopite locally mined for vermiculite	Palabora complex oval area 4
oughly circular and about 1 mile in diameter elike masses of carbonate occur in other rocks	Both calcite and dolomite reported; apatite and magnetite locally abundant	Oval area 3 by 2 miles
foot wide and 1100 yards long traverses sev-	Banded character of vein noted; pyrrhotite is principal sulfide mineral	Dike complex
odies of calcitic carbonate in the Kimberly about 60 feet thick	Calcite is principal carbonate mineral, but dolomite and ankerite also present; accessory minerals include apatite, magnetite, sphene, and serpentinized olivine	Oval pipe about ½ mile in di
up to 800 meters long and 300 meters wide	Apatite, magnetite, and biotite locally abundant; pyrochlore identified in rock	Oval area about 20 square mi

kalic complex	Geologic age	Petrologic relationships
	Probably part of late Paleozoic Fennoscandian alkalic petrographic province	Essexite later followed by ijolitic and other nepheline-bearing rocks; carbonatites younger than most of the igneous rocks; fenite well developed at border of complex; country rock is Precambrian
ıtacts extrapolated across	Late Jotnian age according to Eckermann; probably belongs to late Paleozoic Fennoscandian alkalic province	Border area essentially fenite, quartz syenite, and syenite; central area essentially nepheline-bearing felsic and mafic rocks; arcuate pattern of carbonatite cone sheets on Alno Island and massive sovite on offshore islands; radial pattern of younger alnoite dikes; country rock is Precambrian
	Tertiary; probably part of Alpine Tertiary alkalic province	Development of the Rhine graben followed by several magmatic episodes: (1) intrusion of essexite and theralite; (2) extrusions of tephrite; (3) dike rocks, principally phonolite and monchiquite. Marble long believed to be altered xenolith in caldera
	Cretaceous according to Ross; probably part of Cretaceous Midcontinent alkalic province	Earliest rocks include mafic and felsic feldspathoidal rocks containing nepheline or pseudoleucite; younger mass of uncompahgrite (melilite rock) altered to vesuvianite-rich rock resembling that in Iron Hill stock; carbonatites are youngest in sequence and have altered nepheline syenite locally to vesuvianite-diopside rock; country rock is Paleozoic
	Pre-Jurassic(?) or Tertiary(?)	Biotite pyroxenite constitutes 70 per cent of stock; younger rocks include uncompahgrite, nepheline and soda syenite, and nepheline gabbro dikes; age of main Iron Hill carbonatite not established, but Larsen believes it to be oldest rock in stock; dikelike bodies of carbonate rock occur in other rocks and presumably youngest in sequence; country rock is Precambrian
ile	Precambrian, based on zircon and monazite ages by Jaffe	Several intrusive masses of shonkinite, syenite, and potassic granite in the district; carbonatites are younger than the alkalic rocks; country rock is Precambrian
	Eocene, based on fossil evidence in correlated volcanics; part of the Central Montana alkalic petrographic province	Sequence in Rocky Boy stock is: (1) biotite pyroxenite (2) nepheline shonkinite and shonkinite and related syenites; (3) alkalic monzonite; (4) nepheline-aegirite syenite with pegmatites; (5) porphyritic potassic syenite with carbonatites; (6) olivine-leucite phonolite dikes. Country rock is Cretaceous and Tertiary (early Eocene) sedimentary rock
	Late Tertiary; part of the Mt. Elgon chain	Volcanic plug composed of mafic to felsic nepheline-bearing and melilite-bearing rocks with core of carbonate rock; volcanic pile also contains some andesite near base; original cone estimated to be 24 miles in diameter and 10,000 feet high; 97 per cent removed by erosion; country rock is Precambrian
ess than Napak	Late Tertiary; part of the Mt. Elgon chain	Not described in detail but probably similar to Napak
	Late Tertiary; earlier than Mt. Elgon tuffs	Syenite and nepheline-bearing syenite observed in poorly exposed ring between carbonate core and fenitized Precambrian country rock
gest in Uganda	Late Tertiary; earlier than Mt. Elgon tuffs	Complex composed of biotite pyroxenite, nepheline-bearing rocks, syenite, and magnetite-apatite-biotite rock between carbonate rock and fenitized Precambrian country rock
ı diameter	Late Tertiary; earlier than Mt. Elgon tuffs	Some magnetite-apatite-biotite rock exposed between carbonate rock and fenitized Precambrian country rock. Complex may be three volcanic necks
ı diameter	Late Tertiary	Biotite pyroxenite and nepheline-bearing felsic rock exposed beyond border of carbonate rock but within fenitized border of complex
niles in diameter	Miocene, based on fossil record in related volcanics	Kisingiri volcano composed of tuff, agglomerate, flows, dikes, and plugs of nepheline-bearing ijolitic and phonolitic varieties; main plug of Rangwa Hills contains brecciated as well as massive rocks including carbonate rock
niles in diameter	Tertiary(?)	Petrology of Ruri Volcano not described but probably similar to Kisingiri
miles in diameter; sev-ry vents	Late Tertiary	Homa volcano composed of multiple eruptions of tuff, agglomerate, and flows of nepheline-bearing rock; nepheline-rich plug rock contains plugs and dikes of sovite breccia; later eruptions include more alkalic rock and more carbonate rock; country rock is Precambrian
½ miles	Tertiary(?)	Principal complex of Jombo composed of mafic and felsic nepheline-bearing rocks; three separate agglomerate vents occur in arc 5 miles east of Jombo complex; carbonatite believed to be related to eruption of one subsidiary vent at Mrima Hill; country rock is Mesozoic sedimentary sequence
00 feet in diameter	Mesozoic(?), part of Chilwa volcanic series	Complex composed of volcanic tuff, agglomerate, and vent breccia with abundant carbonate rock. Complex is interpreted as an explosive vent in the Precambrian gneiss
es	Mesozoic(?), part of Chilwa volcanic series	Principal vent material is olivine nephelinite and carbonate rock. In area 70 by 130 miles south and southwest of Lake Chilwa are more than 16 vents, 9 of which contain some or much carbonate rock. These vents are designated the Chilwa Series by Dixey, and they pierce the Precambrian
es	Mesozoic(?), part of Chilwa volcanic series	Vent complex composed of nepheline syenite, agglomerate, and carbonate rock; dikes of later nepheline-bearing rock occur in and beyond the vent complex; country rock is Precambrian
aped 4 by 2 miles	Mesozoic(?), part of Chilwa volcanic series	Vent complex composed of nepheline syenite with some dikes of pegmatite, microfoyaite, tinguaite, and phonolite; agglomerate and carbonate located in western part of complex; country rock is Precambrian
e	Mesozoic(?), part of Chilwa volcanic series	Vent complex composed of agglomerate, nepheline-bearing rock, and carbonate rock; phonolite dikes cut complex and Precambrian country rock
in diameter	Mesozoic(?), part of Chilwa volcanic series	Vent complex in Karroo sandstone forms conspicuous basin-shaped, steep-sided, craterlike depression some 600 feet deep; core composed of crystalline limestone, agglomerate, and younger dikes of nephelinite and phonolite; border area concealed by talus slopes
	Not known	Complex not well exposed; carbonate rock surrounded by ring of fenitized Precambrian gneiss
diameter	Not known; perhaps Mesozoic	Complex composed of biotite pyroxenite, jacupirangite, ijolite, syenite, with outer zone of fenite; country rock is Precambrian
	Not known; perhaps Mesozoic	Complex composed of biotite pyroxenite, shonkinite, syenite, and nepheline-bearing rocks; country rock is Precambrian
	Not known; post-Karroo(?)	Complex composed of nepheline-rich rocks bordered by fenitized Precambrian granite; dikes of mafic and felsic nepheline-bearing rocks and carbonate rocks occur beyond the border of the complex
area 4 by 2 miles	Precambrian(?)	Complex marked by zonal distribution of rock types from border inward including syenite, shonkinite, biotite pyroxenite, "phoscorite" (apatite-magnetite-biotite rock), and carbonatite; dolerite dikes cut the complex and Precambrian granite country rock
	Post-Bushveld; Precambrian(?)	Complex composed of established sequence of rock types: theralite, biotite pyroxenite, ijolite, foyaite, tinguaite, and carbonatite; umptekite at border of complex interpreted as fenitized older Precambrian so-called Red Granite
	Post-Bushveld; Precambrian(?)	Five diatremes of carbonate-bearing agglomerate alined NW. in Bushveld gabbro and cut by carbonatite dike
in diameter	Cretaceous(?)	Brecciated kimberlite pipe containing great variety of xenoliths of basement rocks; contains dikes of kimberlite and dikelike bodies of carbonate rock
re miles	Early Mesozoic	Alkalic province in southeastern Brazil represented by many localities of nepheline-bearing intrusive and extrusive rocks; at Jacupiranga biotite pyroxenite, nepheline-biotite pyroxenite (jacupirangite), and ijolite crop out near the carbonatite exposure

Brögger, 1921, p. 150–152) have been resurrected by many who have concluded that reaction of the invasive alkali-rich fluids and silicic wall rock formed syenite and quartz-bearing syenite. In some places, where the border of a complex is concealed, it has been ascertained from the circular distribution of the syenite.

Some of the silicate minerals in the carbonatites are not unlike those in the associated igneous rocks, and some accessory minerals are common to both. Calcite is a common accessory mineral in the intrusive and extrusive alkalic rocks. According to Bowen (1924), the silicate minerals in the carbonatites of the Fen area show abundant petrographic evidence of attack and corrosion. Rarely, as in the Bearpaw Mountains occurrence, the feldspar crystals are coarse and euhedral, and the feldspar, biotite, and calcite display a well-defined zonal distribution within the carbonatites.

Most of the European writers still employ individual rock names for the different kinds of carbonate-silicate rocks based on the abundance of calcite or dolomite and the identity of the silicate minerals. Sövite, for example, is a massive calcitic carbonatite, and alvikite is its dike equivalent; rauhaugite is the massive dolomitic carbonatite, and beforsite its dike equivalent; ingite contains aegirite and feldspar; kaesinite contains nepheline and pyroxene. All may contain biotite. These names are adopted by many recent authors and graphically illustrated by Von Eckermann (1948, Figs. 1, 2).

The chronologic position of the carbonatites in the sequence of events that characterize the development of the alkalic complexes has been established at several localities and is summarized in Table 1. In general the carbonate rock is the youngest "intrusive" rock in complexes. At some localities, as at Alnö, dikes of alkalic rock are younger than the carbonatites. At others, as at Homa Mountain, multiple episodes of carbonatite dikes and breccia occur in the sequence. The field relations of the dikelike bodies of carbonate rock perhaps offer the strongest support for fluid injection as a mode of formation.

Geologic Age

The geologic age of the carbonatite-bearing complexes has been established within narrow limits for only a few occurrences. For most of the complexes listed in Table 1 the country rock is Precambrian, and the geologic relations visible are inadequate to indicate the age of the igneous activity. Perhaps the most reliable kind of dating is obtained from the fossil record in the sediments in volcanic piles correlated with the intrusive complexes, as has been done, for example, for the Miocene of western Kenya (Shackleton, 1951), the late Tertiary of Uganda (Davies, 1947), the Eocene of Montana (Brown and Pecora, 1949), and the Cretaceous of Arkansas (Ross *et al.*, 1929). Geologic field relations offer little hope for satisfactory dating for application to the broader problem of development of the petrographic provinces and relation to orogeny. New geochemical techniques offer some promise. Inasmuch as uraninite is rare or absent in these alkalic provinces, techniques utilizing other minerals may be fruitful. Use of the Larsen method (Jaffe, 1955) in determining the probable Precambrian age of monazite and zircon from Mountain Pass could be attempted in other areas. Uranium-bearing pyrochlore may be another suitable mineral. New advances in the potassium-argon method and the rubidium-strontium method may lead to the use of biotite, feldspar, and other such common minerals.

Relation to Volcanism

In his review of the mechanism of emplacement of alkalic rock complexes Backlund (1932) emphasized the requirement for perforation of stable areas (epeirodiatresis) in contrast to the orogenic relation of granite batholiths and epeirogenic relation of basaltic floods. Many writers have supported his analysis that the alkalic complexes then known might have been the roots of ancient volcanoes. Ross and others (1929, p. 189–202), in the absence of volcanic rocks in south-central United States, attributed the volcanic materials in Cretaceous formations in that region to widespread volcanism from several conduits in the Ouachita Mountains area, and among them is the Magnet Cove complex (Ross, 1941, p. 24).

The important paper by Dixey and others (1935) on the Chilwa Series of southern Nyasaland was apparently not widely known until more recent publications on volcanic centers in

East Africa. Carbonatite-bearing volcanic plugs and breccia pipes in East Africa representing partly or completely denuded volcanoes are now well known as a result of the work of several British geologists. The idea is well supported, at least, that alkalic complexes in Shield areas may represent the eroded roots of ancient volcanoes.

For those carbonatite-bearing volcanoes, King's (1949, p. 51, 55) term of "carbonated magma" for the Napak volcano in Uganda may be very appropriate for the many others in East Africa. The amount of carbonate present in carbonatites, in tuffaceous beds, in vesicles, in agglomerate, and in the groundmass of igneous rocks is impressive. But as the volume of erupted material in the Rift Valley alkalic province is measureable in many hundreds of cubic miles, the proportion of visible carbonate to igneous rock is insignificant. It is not unreasonable to assume that the carbonatites are related to the periodicity of volcanic eruption.

Composition

Provisional Classification

Recent information suggests two mineralogical varieties of carbonatites that differ greatly in their accessory-mineral assemblage. One may be referred to as the apatite-magnetite variety, and the other as the rare-earth minerals variety. Modifications of each exist, and gradations between the varieties may be more common than is now apparent. The difference in mineral assemblage seems to be merely a difference in the relative concentrations of some rare elements. A conspicuous, and seemingly important, difference in the igneous-rock association of the two varieties is the genetic association of the apatite-magnetite variety with feldspathoid-bearing rocks and of the rare-earth minerals variety with more silicic alkalic rocks.

The apatite-magnetite variety is the more widely represented and includes such classic localities as Fen, Alnö, Kaiserstuhl, Magnet Cove, and several African localities. Accessory minerals containing titanium and niobium are also present, and among them perovskite, pyrochlore, melanite, and rutile are most common.

The rare-earth minerals variety is best represented by the carbonate-rich rocks at Mountain Pass, California, in which the accessory-mineral assemblage is characterized by rare-earth fluocarbonates (chiefly bastnaesite), the rare-earth phosphate (monazite), and barite. Apatite, magnetite, titanium minerals, and niobium minerals are absent or extremely rare. A modification of this variety is perhaps represented by those deposits in the Bearpaw Mountains where the principal rare-earth mineral is burbankite (Pecora and Kerr, 1953). Detailed studies of African carbonatites may clarify the distinction, if any.

Mineral Composition

More than 50 minerals have been reported from the carbonatites. This class of rocks is probably made up of 80 per cent or more of the simple and complex carbonate minerals. Among the simple carbonates calcite is dominant, dolomite next in abundance, and ferruginous and manganiferous carbonates, including siderite and ankerite, are least abundant. Most of the complex carbonates are the rare-earth bearing ones and include bastnaesite, parasite, synchisite, roentgenite, burbankite, calkinsite, lanthanite, ancylite, and sahamalite.

Silicate minerals include orthoclase, microperthite, albite, nepheline, augite, diopside, aegirite, forsterite (and serpentine), monticellite, biotite, phlogopite, vermiculite, garnet (melanite), melilite, chondrodite, sphene, and cerite.

Phosphate minerals include fluorapatite, monazite, and isokite. Simple oxides include magnetite, hematite, ilmenite, rutile, anatase, brookite, and baddeleyite. Sulfides include pyrite, pyrrhotite, chalcopyrite, galena, tetrahedrite, molybdenite, bornite, chalcocite, and valleriiete. Barite is the principal sulfate mineral. Other minerals include pyrochlore, perovskite, sellaite, zircon, and fluorite.

At Alnö and Fen, some carbonate-rich rocks are almost all calcite or all dolomite, but others show a range of admixture of calcite and dolomite. In bulk, however, the calcite carbonatite (sövite and alvikite) predominates over the dolomitic variety (rauhaugite and beforsite). The maximum modal mineral percentages given by Von Eckermann (1948, p. 64–140) and Brögger (1921, p. 401–403) for a

great number of analyzed carbonate-rich and silicate-carbonate carbonatites in these two districts are as follows:

	Alnö	*Fen*
Calcite	97	93
Dolomite	81	90
Alkali feldspar	72	65
Pyroxene	31	50
Biotite (and phlogopite)	47	27
Olivine (and serpentine)	15.8	?
Apatite	16.4	16.4
Magnetite	9.5	8
Melanite	19	5.8
Perovskite	4.2	?
Pyrochlore (and microlite?)	2.1	1.4

The proportion of calcite to dolomite in carbonatites of many other regions varies also within wide limits. The carbonate at Iron Hill, Colorado, according to Larsen (1942, p. 5), is dominantly dolomite. At Spitzkop (Strauss and Truter, 1951a) the central part of the carbonate mass is dolomitic, and the outer part calcitic. Shand (1931) reports that at Loolekop dolomite is more abundant than calcite, and that the marble contains 75 per cent carbonate minerals, 20 per cent olivine and apatite, and 5 per cent magnetite. For one analyzed specimen from Chishanya, Swift (1952, p. 350) calculates 17.6 per cent apatite, 6.2 per cent magnetite, 5.1 per cent silicates, and 69.7 per cent carbonates, with calcite 4 to 5 times more abundant than dolomite. For many of the carbonatite cores of volcanic necks in East Africa, calcite is reported as abundant, presumably more so than dolomite, although some parts of these cores contain discrete grains of ferruginous and manganiferous carbonate. Dixey and others (1935, p. 7–13) show that in four such cores (Chilwa Island, Tundulu, Kangankunde, Muambe) the manganese content ranges from about 2 to 15 per cent (10 analyses) and iron from about 3 to 50 per cent (6 analyses). It is not stated, however, whether these samples were fresh or oxidized.

At Magnet Cove, two kinds of carbonate-rich rock are known. One variety, exposed in the Kimsey Quarry, was originally described by J. F. Williams (1890, p. 330–341) and resembles the coarsely granular occurrences at Kaiserstuhl and elsewhere. Monticellite is the principal silicate in the marble at the Kimsey Quarry, and the mineral identified as olivine in some carbonatites elsewhere in the world may well be monticellite, which it closely resembles in optical properties. A second kind of carbonate-rich rock at Magnet Cove, more recently described by Fryklund and Holbrook (1950, p. 26–36) and Fryklund and others (1954, p. 29–34), is known as the "rutile deposit" and comprises an intricate network of rutile-bearing veins that are classified as albite-dolomite, microcline-calcite, microperthite-albite-carbonate, and calcite varieties. A concentration of rutile and pyrite is characteristic of this variety of carbonatite. The Magnet Cove stock is currently under reinvestigation by members of the U. S. Geological Survey.

The barite-carbonate rock in the entire Mountain Pass district is estimated by Olson and others (1954, p. 29–30) to contain about 60 per cent carbonate minerals, 20 per cent barite, 10 per cent bastnaesite and other rare-earth minerals, and less than 10 per cent of other minerals including quartz. The principal deposit, called the "Sulphide Queen" and estimated to be more than 10 times larger than the sum of all the exposed veins in the district, is estimated to contain almost 15 per cent rare-earth minerals. Of all carbonatite occurrences known, that at Mountain Pass contains the highest concentration of rare earths, barium, and strontium. The carbonate veins in the Bearpaw Mountain locality likewise contain rare-earth minerals and barite (Pecora and Kerr, 1953) but not in such great concentration as at Mountain Pass. At these two localities the carbonate rock contains few or none of the accessory minerals common in other carbonatites, such as apatite, magnetite, pyrochlore, and pervoskite.

Chemical Composition

The variation in chemical composition of 80 published analyses of carbonate-rich and silicate-rich carbonatites is given in Table 2. This range is a true reflection of the variation in composition between those alkalic rocks containing a substantial amount of carbonate and those carbonate rocks containing little of the silicate and other minerals. The analyses of rocks from East Africa show less variation than do those of rocks from Alnö and Fen, but this

may be more coincidence of original sample selection than a real distinction between the two regions. One might interpret the geologically younger occurrences in East Africa, however, as being in vertical dimension much nearer the vents of their parent extinct volcanoes. Inspection of the variation in CO_2 also supports a hypothesis of mutual origin of this peculiar group of rocks by some orderly process that would tend to concentrate CaO and CO_2 after earlier separation of SiO_2 and Al_2O_3 in the silicate rocks.

Table 2.—Variation of 80 Published Chemical Analyses of Carbonatites

	Alnö* (49 analyses)	East Africa† (21 analyses)	Fen** (10 analyses)
SiO_2	0.1–49.6	0.3–17.2	0.73–35.86
TiO_2	Tr–4.5	0.2–0.4	0.12–2.51
Al_2O_3	0.2–18.2	0.18–3.7	0.60–6.57
Fe_2O_3	0.1–8.0	0.12–9.4	0.53–7.26
FeO	0.1–10.5	0.23–8.9	0.67–9.14
MgO	0.1–15.3	0.8–18.8	1.62–10.59
CaO	4.0–55.4	24.1–54.5	25.35–50.47
Na_2O	0.03–2.3	0.01–0.9	0.01–2.21
K_2O	0.03–12.8	0.02–1.2	0.17–3.62
P_2O_5	0.6–4.8	0.13–5.5	0.95–6.92
CO_2	3.1–43.1	24.2–43.7	6.99–42.88
H_2O^+	0.1–2.3	0.2–1.5	0.04–0.37
S	0.01–20.3	0.16–0.44	0.07–0.67
F	0.06–2.4	0.02–0.3	0.08–0.56

* Includes carbonatities rich in silicate and non-carbonate minerals; von Eckermann (1948, p. 74–78, 113–122, 128–137)

† King (1949, p. 44); Saggerson (1952, p. 81); Strauss and Truter (1951, p. 114, 187); Fockema (1953, p. 168); Fawley and James (1955, p. 576; Nb_2O_5 in 7 analyses from Mbeya range 0.1 to 0.9)

** Brögger (1921, p. 400–401; Nb_2O_5 plus Ta_2O_5, 0.07–0.82 in 4 analyses)

Geochemical Distribution

General.—The exceptional concentration of CO_2 in carbonatites coupled with extraordinary concentrations of such rare constituents as barium, strontium, and rare earths (Table 3) shows a more pronounced geochemical affiliation with the alkalic rocks than with other igneous-rock assemblages. Although CO_2, barium, strontium, the rare earths, and niobium show a many-fold concentration in carbonatites compared with alkalic rocks, elements such as titanium and phosphorus do not. Zirconium and hafnium have their greatest concentration in alkalic rocks rather than in carbonatites. The wide range of the major elements in analyzed carbontite samples (Table 2) is meaningless except as an illustration of the variety in this group of rocks.

Table 3.—Relative Abundances and Variation of Some Rare Constituents in Different Rock Assemblages

In weight per cent; data summarized from several published and unpublished sources by Pecora

	All igneous rocks	Gabbro	Alkalic rocks*	Carbonatites†
Ce_2O_3**	0.005	0.0005	0.01–0.05	0.02–?
BaO	0.03	0.02	0.1–1.0	0.5–10
SrO	0.03	0.02	0.1–1.0	0.5–2
Nb_2O_5	0.0005	0.002	0.001–0.05	0.001–0.5
Ta_2O_5	0.0002	0.0001	0.0001–0.001	?
ZrO_2	0.03	0.01	0.04–0.2	0.001–0.02
TiO_2	0.8	1.5	0.5–2.0	0.1–3
P_2O_5	0.3	0.3	0.2–2.0	0.1–6
F	0.05	0.03	0.01–0.2	0.02–2.4
CO_2	0.10	0.05	0.2–2.0	3–43
S	0.05	0.2	0.1–0.3	1–10
H_2O	1.5	1.5	1–3	0.1–1

* Includes biotite pyroxenite, biotite, peridotite, mafic and felsic feldspathoidal rocks

† Includes silicate-carbonate rocks

** Includes all rare earths

The distribution of the rare constituents follows different patterns, for in some carbonatites they form the major ingredients of some minerals, and in others they are substituents for elements with similar ionic radii in other minerals. For this reason certain minerals may have diagnostic chemical features distinguishing their occurrence in carbonatites from occurrence in other environments. The economic significance of these features is being investigated in many areas.

Barium and strontium.—The geochemical coherence of barium and strontium is well known (Rankama and Sahama, 1949, p. 109–111), and the selective concentration of this pair of elements in alkalic igneous rocks has been demonstrated by many writers. (*See also* Table 3.) In

some carbonatites, however, strontium is selectively concentrated over barium as shown by Higazy (1954, p. 63) and Russell and others (1954, p. 201). Values for strontium reported by these authors range from 2500 to 7750 ppm and

TABLE 4.—RELATIVE ABUNDANCES (in per cent) OF RARE-EARTH METALS IN "CERIUM" MINERALS FROM MOUNTAIN PASS, CALIFORNIA, AND BEARPAW MOUNTAINS, MONTANA

(Spectrographic analyses by H. J. Rose, U. S. Geol. Survey)

	Mountain Pass, Calif.*				Bearpaw Mtns., Mont.†	
	Bastnaesite	Parisite	Monazite	Cerite	Burbankite	Calkinsite
La_2O_3	29.6	29.2	28.6	21.9	25.8	30.7
Ce_2O_3	50.3	49.3	53.7	54.3	53.6	52.0
Pr_2O_3	4.4	4.2	4.4	5.7	4.2	4.5
Nd_2O_3	14.3	13.7	11.9	16.1	15.4	12.3
Sm_2O_3	1.3	1.3	1.2	1.5	1.1	0
Gd_2O_3	0	0.0	0	.44	.84	0
Y_2O_3	0	0.15	0	.60	1.1	0
Total	99.9	97.9	99.8	100.54	102.0	99.5

Note: Limit of detection: Sm_2O_3, 0.6; Gd_2O_3, 06; Y_2O_3, 0.1

* From Murata *et al.*, report in progress

† *See also* Pecora and Kerr (1953, p. 1173, 1178)

for barium from 88 to 1985 ppm. Because of the closeness of ionic radii, strontium (1.27Å) is a common substituent for calcium (1.06Å) in the apatite and calcite of carbonatites. Von Eckermann (1952, p. 368, 370) reports higher concentration of barium than strontium for rocks and minerals at Alnö Island. The selective concentration of barium over strontium appears to be specific for the potassium-rich minerals (biotite and orthoclase) in the rocks intimately associated with the carbonatites.

Where sulfate occurs in the carbonatites, as at Mountain Pass and in the Bearpaw Mountains, barite is much more abundant than celestite. At Mountain Pass, barite is abundant enough to make the carbonate rock a barite ore as well as rare-earth ore (Olson *et al.*, 1954, p. 34). Barite constitutes up to 65 per cent of the rock locally, is strontium bearing, and far exceeds the celestite in quantity within the ore body.

Niobium (*columbium*).—Niobium (columbium) and tantalum are strongly coherent elements that concentrate together in most igneous rocks. As summarized by Rankama and Sahama (1949, p. 606) the Nb/Ta ratio in most igneous rocks ranges from 0.4 to 17.3, but in the few alkalic rocks analyzed it is 387. Although our available sampling information is meager, it would seem that the Nb/Ta ratio in carbonatites is also high. Is there a real problem indicated as to the selective concentration of Nb over Ta in the formation of alkalic igneous rocks and the carbonatites?

The principal niobium-bearing mineral in carbonatites is pyrochlore, essentially a calcium niobate poor in tantalum. The cerium-rich variety of pyrochlore has been called koppite. The microlite referred to by Brögger as occurring in the Fen carbonatites was later shown by Björlykke (1934) to be poor in tantalum and hence more properly pyrochlore. Substitution of niobium for titanium is substantial in some titanates in alkalic rocks and carbonatites. As shown by Fleischer and others (1952) a few per cent of Nb is not uncommon in rutile, brookite, and anatase, and up to 18 per cent is found in those varieties of perovskite called dysanalyte (niobian perovskite) and knopite (cerian pervoskite).

The niobium-bearing minerals variously referred to as pyrochlore, koppite, perovskite, dysanalyte, and knopite are only accessory minerals in both the carbonate rock and silicate rocks at many carbonatite localities. Their greatest concentration has been noted in the carbonatites, however, and several localities offer promise of a substantial reserve suitable for production of a marketable mineral concentrate rich in niobium. Published results of exploration are available for deposits at Fen, Kaiserstuhl, and the Mbeya carbonatites, but activity is also in progress at many other localities.

Björlykke (1955) reports a monthly production of 15 tons of concentrate averaging 50 per cent Nb_2O_5 from the Fen deposit and mentions plans for increasing the production to 30 tons a month. The potential reserve of ore there is estimated as several million tons, and drill-core samples show a range of 0.2 to 0.5 per cent Nb_2O_5. Analyses of pure pyrochlore crystals

(Björlykke, 1955, p. 413) show 59 to 62 per cent of the pentoxide. In some samples where columbite is an alteration product the Nb_2O_5 content is as high as 74 per cent. From several 500-gram samples of the Kaiserstuhl carbonatite Metschke (1938) recovered 0.35 to 1.6 per cent concentrate of pyrochlore and niobium-bearing perovskite, and Leibrandt (1948) calculated from analyses of drill cores in the same deposit a reserve of several thousand tons of carbonate rock containing not less than 0.2 per cent Nb_2O_5. At Mbeya (Panda Hill) 4630 feet of diamond drilling indicates (Fawley and James, 1955, p. 583–585) a reserve of pyrochlore-bearing carbonatite in excess of 11 million tons with an average of about 0.3 per cent Nb_2O_5. Fryklund and others (1954, p. 47) report that niobium was detected in only 6 of 21 carbonatite channel samples taken at the Kimsey Quarry at Magnet Cove and that the samples show a range of 0.01 to 0.07 per cent Nb. Extensive exploration in the carbonatite areas near Tororo Station in eastern Uganda has demonstrated a substantial reserve of surficial material concentrated and altered by weathering that likewise contains an appreciable reserve of pyrochlore and other heavy minerals. Drilling and sampling are currently in progress at several sites in Africa, Europe, Canada, and Brazil. The pyrochlore at many localities commonly contains a fraction of a per cent of uranium, and prospecting for uranium with Geiger counters has aided in the discovery of uranium-bearing pyrochlore at some places.

Recovery of niobium, rare earths, titanium, and uranium from the pyrochlore concentrates from these deposits poses a tremendous challenge to metallurgists. In view of the great magnitude of reserves of this kind of material, however, industry will undoubtedly attempt to solve this problem. Most of the world's niobium supply has been obtained from columbite in granitic pegmatites. The writer has great confidence that in view of the tremendous potential reserve of pyrochlore in carbonatites and many alkalic rocks the future supply of niobium may well be recovered largely from the alkalic provinces.

Rare earths.—Goldschmidt (1937, p. 662–665) pointed out the relatively higher concentration of the rare-earth metals in alkalic rock than in other rocks. In most carbonatites this concentration is even higher (Higazy, 1954, p. 63). At Mountain Pass the rare-earth content in the carbonate rocks is truly exceptional. For the Sulphide Queen ore body, Olson and others (1954, p. 64) report a range of the rare earths from less than 1 to about 38 per cent, and for the district an average of 5–10 per cent. In the Bearpaw Mountains carbonatite samples from three veins have as much as 3.5 per cent rare earths. Several African deposits are also known to contain rare-earth minerals. The realization that carbonatites are a potential source of rare-earth metals is a relatively recent and important discovery. Lanthanum, cerium, praseodymium, and neodymium are in much greater abundance than the other metals of the group, as illustrated by selected mineral analyses in Table 4. Investigations in progress by members of the U. S. Geological Survey on the distribution of rare-earth elements in cerium minerals as determined by analysis and synthesis will be published soon.

The chemical affinity of the rare earths for phosphorus and fluorine in an environment rich in Ca and CO_2, as exists in carbonatites, is diagnostic of their distribution. They are the principal metals in many carbonates, fluocarbonates, and phosphates. When such minerals are rare or absent in carbonatites, the rare earths are commonly a substituent for calcium in perovskite, pyrochlore, and apatite, and, in less amount, in calcite itself.

Phosphorus.—Although phosphorus and titanium are not a geochemically coherent pair of elements, their concentrations in igneous rocks follow the same general pattern. Both have a moderate tendency toward higher concentrations in alkalic rocks and carbonatites (Table 2). Both are concentrated in varieties of biotite pyroxenite occurring in some alkalic complexes as reported by several authors (Du Toit, 1931; Larsen, 1942). In the carbonatites phosphorus generally exceeds titanium.

The search in many areas for sources of phosphate and limestone for agricultural and industrial uses has led to much systematic study of some carbonatites, particularly in Fennoscandia, Brazil, and East Africa. Davies (1954), for example, reports that 640 analyzed carbonatite samples from the Tororo Hills average 1.725 per cent P_2O_5, and 961 from Sukulu average 3.68 per cent P_2O_5. Both carbon-

ate rocks have more than 80 per cent $CaCO_3$. The phosphorus here is essentially in the mineral apatite, as it is in the 80 analyzed samples of carbonatites summarized in Table 2. At Mountain Pass, however, apatite is rare or absent in most of the carbonatites, and the phosphorus has combined with the rare earths to form monazite.

In those alkalic complexes containing both biotite pyroxenite and carbonatites phosphorus is more highly concentrated in an intermediate rock type composed essentially of biotite (or phlogopite), magnetite, apatite, calcite, and ferromagnesian silicates. Russell and others (1954, p. 199–200) refer to this rock in the Palabora complex as "phoscorite", and they report up to 10 per cent P_2O_5 in some samples. This rock type, a potential source of apatite and vermiculite, is common in many alkalic complexes as a variety of the pyroxenite.

Zirconium.—Although zirconium is most highly concentrated in certain alkalic rocks in contrast to other igenous rocks (Fleischer, 1955), this element, unlike the others mentioned above, is relatively more abundant in the silicate rocks than in the associated carbonatites. Zircon and baddeleyite have been identified in the residual surface material at some Brazilian and African localities. Russell and others (1954, p. 200) describe baddeleyite from Loolekop, and Higazy (1954, p. 63) reports 70–90 ppm of zirconium in other carbonatites. Zirconium is more selectively concentrated as zircon and as a substituent in silicate minerals in the syenitic facies of alkalic complexes than in the carbonatite facies. In residual mantles zircon from several rocks can easily concentrate as a heavy mineral in the detritus along with pyrochlore, monazite, and other resistant minerals.

Xenoliths and Skarns

Metamorphosed carbonate rock occurring as xenoliths in alkalic igenous rocks or as skarns in contact with intrusive alkalic rocks have been reported by many. Most of these occurrences have been summarized by Daly (1910; 1918) and Shand (1931; 1945) who have cited them in support of limestone-assimilation hypotheses for the origin of the alkalic rocks.

In 1950, David Gallagher and this reviewer re-examined the so-called "xenoliths" in the Magnet Cove complex and were convinced of their dikelike (or veinlike) relations with the reportedly younger nepheline syenite. Inclusions of nepheline syenite in the carbonate rock and wall rock of syenite adjoining the carbonate rock exhibit zoned contact-metamorphic effects in the formation of vesuvianite, diopside, melanite, and magnetite. The fibrous wollastonite reported as abundant by Landes (1931) in the carbonate "xenolith" is in fact fibrous apatite, not wollastonite. Most of the high-temperature skarn suite, such as akermanite, merwinite, and scawtite, are absent in this and other carbonatites. Their absence may suggest temperature rather than compositional differences.

A recent re-examination by Strauss and Truter (1951a) presents evidence that the carbonate rock at Loolekop in the Spitzkop complex is likewise intrusive, not xenolith as earlier reported by Shand (1931).

As an interesting reversal of the trend to convert xenoliths into carbonatites, Björlykke (1955, p. 412) quotes Svinndal, resident geologist at Söve, as concluding that the large bodies of carbonatites in the Fen district are contact-metamorphic in origin. The controversy becomes all the more fascinating if the type locality of carbonatites is no longer a stronghold for the Bröggerian magmatists.

In other areas, however, alkalic igneous rocks are known to be intrusive into sedimentary limestone formations. Allan (1914) has described such a situation for the Ice River complex. He reports pronounced contact-metamorphic effects in the early Paleozoic Ottertail formation induced by sills of alkalic rock and describes xenoliths in the sill occurring as blocks as much as 100 feet long. Xenoliths in the stock are much larger; the largest, at Garnet Mountain, is 1250 feet by three-fourths of a mile. Several hand specimens of igneous and skarn rocks supplied to the reviewer by Dr. W. H. Patmore display many features characteristic of skarn mineralization, particularly in a "nodular" brown garnet development. Other skarn specimens, however, contain pyrochlore. Allan (1914, p. 117) has reviewed the detailed mineralogy of the altered carbonate rocks.

It is not yet certain whether the mineral associations induced by contact metamorphism of limestone and dolomite by alkalic magmas is

the same as that in carbonatites. Differences occur in compositional varieties of some minerals or absence in one environment of certain minerals that appear in the other. In the Bearpaw Mountains, the writer has distinguished the skarns and carbonatites by their distinctive field relations as well as by differences in mineral composition.

Thus, detailed field investigations may establish more carbonatites at several localities where carbonate rock and alkalic igneous rocks occur together, as in the Lake Nipissing area of Ontario (Rowe, 1954a); the Oka Hills district of Quebec (Rowe, 1954b); the Kalkfeld-Okorosu area of South West Africa (Stahl, 1930; Gevers, 1933); Kuolajarvi district, Finland (Hackman, 1925). The search for niobium and rare earths may lead to much more directed field examinations in many alkalic provinces, for it is a well-recognized principle that an intrusive rock normally offers greater tonnage than a xenolith with the same exposure area. Even if further work shows that the two different geological processes—fluid intrusion as opposed to contact metamorphism—yield the same general mineral association or even the same excellent chance for ore deposits, the reviewer suggests that the term carbonatite not be used for the contact-metamorphic environment.

An interesting facet of the problem is suggested in the field relationships described by Swift, Fockema, Shackleton, and Strand. Swift (1952), in describing the area near Chishanya, Southern Rhodesia, reports outliers of carbonate rock in the district which he assigns to a limestone formation, 30–300 feet thick, that is part of the Umkondo sedimentary sequence, older than the Karroo series and younger than the Precambrian granite basement. Yet he maps these outliers separately from the isolated carbonatites outside the Chishanya alkalic complex. Fockema (1953) describes the relationships of a large xenolith of the Transvaal dolomite, 2 by 4 miles, in the Bushveld granite near Pretoria. Dolomite dikes, termed beforsite by Fockema (1953, p. 166–168), occur in an arcuate zone and intrude both the granite and the xenolith. Shackleton (1951) reports blocks of granite and carbonate rock in agglomerate and breccia on Rusinga Island that came from the Kisingiri vent in western Kenya—one of the vents characterized by a core of carbonatite. On the island of Stjernoy in the basic province of northern Norway, a biotite sövite about 1 square mile in area, containing 1–10 per cent apatite, exhibiting a pronounced banding, and surrounded by gabbro, is interpreted by Strand (1951) to be a carbonatite like those at Fen and Alnö. The field relations reported by these geologists suggest that parts of sedimentary carbonate formations digested in place, rafted up from below, or foundered from above, may indeed provide the principal constituents for later residual carbonatic fluids or may provide the principal means for making alkalic rocks themselves as held by Daly and Shand.

Experimental Investigations

In recent years an increasing amount of experimental inquiry has been undertaken at several laboratories, and many important papers will continue to be released dealing with presure-temperature relations for carbonate systems. Smyth and Adams (1923) first established the melting point of $CaCO_3$ as 1389°C. at 779,000 mm pressure. This experimental result has helped convince many petrologists that carbonatic magmas cannot exist in nature. Although Harker and Tuttle did not observe glass after quenching (as proof of melting) in their highest temperature-pressure investigations of carbonates, they admit (1955a, p. 223) that glass would not be expected to form from these materials under the experimental conditions. Experience with silicate systems demands that simulated magmas can be quenched in the laboratory to yield glass. If a carbonatic magma cannot exist in the fashion proposed by Brögger and some later European geologists, what is, then, the nature of the carbonatic solutions that do exist at elevated temperature? Hewett (1928) and Faust (1949) have reviewed the heat effects and origin of some magnesia-rich, dilute, hydrothermal solutions in dolomitic environments. Experimentally, Morey and Fleischer (1940) and Miller (1952) record important results on the solubility relations of systems with CO_2 and H_2O. Their work shows that solubility of CaO, K_2O, and SiO_2 increases markedly at an elevated temperature if CO_2 pressure increases. Much chemical work can be accomplished in a

liquid-gas system at high pressures. More recently, Garrels and Richter (1955) introduced an argument that a CO_2-gas phase can accomplish much work even at low temperature and pressure. There is a valid area yet to be investigated wherein hot concentrated solutions rich in CO_2 and under high confining pressures may exist. We need not call this liquid (or liquid-gas) solution a magma, but it certainly would be a carbonatic solution capable of great activity and potentially a source of escaping CO_2 as the pressure is released.

Carbonate minerals in carbonatites may offer some important clues on geologic thermometry. The descriptions of fine-grained exsolution intergrowths of calcite and dolomite by Russell and others (1954, p. 201) and Von Eckermann (1948, Pl. 35) are particularly interesting in view of experimental investigations on solid solution of $CaCO_3$ and $MgCO_3$ by Harker and Tuttle (1955b), Graf and Goldsmith (1955), and Goldsmith and others (1955). The solid solution of strontium in calcite has been synthesized by Faivre (1946), and the conditions of solid solution in carbonates of other elements like barium and rare earths are being currently investigated in several laboratories. Experiments along these lines may yield significant information or limit the physical-chemical conditions of formation of the carbonate minerals in carbonatites.

An inquiry into the relative proportions of the isotopes of oxygen and carbon in carbonate rocks was made by Baertschi (1951) who reported higher values of the heavier isotopes of oxygen and carbon in some typical carbonatite specimens than for most marine sedimentary limestone samples tested. If his results are significant, one interpretation may be that the higher ratios of O^{18}/O^{16} and C^{13}/C^{12} in carbonatites may be some clue for temperature control. In this connection it may be wise to test many more samples whose geologic relationships are well substantiated. Similar investigations by Von Eckermann and others (1952) show little if any systematic variations in C^{13}/C^{12} for carbonate rocks although they detect a lower ratio of C^{12}/C^{13} in the dolomitic dikes (beforsite) than in the calcitic dikes (alvikite). The isotope data are preliminary, and more systematic and controlled geologic sampling is warranted.

Origin

Mode of Formation

In our present state of knowledge on the subject we are quite free to speculate on the origin of carbonatites. Four groups of hypotheses have been offered to explain the mode of formation of carbonatites, and except for requiring elevated temperatures they have not much in common except an impressive array of competent petrologists. The four schools are (1) magmatists, (2) hydrothermalists, (3) xenolithists, and (4) gas transferists.

The concept of "primary" calcite in igneous rocks had been suggested by many writers (as Högbom, 1895; Workman, 1911) well before the appearance of the classic memoir on the Fen area, but it was Brögger's clear expression on the existence of a carbonatic magma that initiated the school of magmatists for carbonatites. He felt called upon, however, to explain the extraordinary amount of CO_2, and this he did by postulating assimilation by an alkalic magma of a sedimentary limestone formation—although none is exposed for miles around. This hybrid magma, nevertheless, followed the normal course of crystallization differentiation to yield liquids so rich in dissolved carbonate that carbonate magma resulted.

Von Eckermann, on the other hand, is not so pure a magmatist. He believes in the validity of a carbonatic liquid (1948, p. 161), composed essentially of potassium carbonate and at a temperature of 400°–600°C., but he believes that this hot liquid induced a chemical exchange with the country rock to produce the alkalic rocks at Alnö essentially through metasomatism. His investigations were perhaps too restricted geographically, for the great volume of alkalic volcanic rocks in other regions would not make unreasonable the existence of large volumes of alkalic magma in the crust. Von Eckermann does not explain the source of the carbonatic liquid but finds some support for its existence and chemical behavior in the work of Morey and Fleischer (1940) on vapor-liquid phases in the system CO_2-H_2O-K_2O-SiO_2.

Although Von Eckermann has avoided the problem of ultimate origin of the carbonatic liquid and concerned himself mainly with tectonics and chemistry after its ascent into the

crust to a critical depth of a few kilometers below the surface, Holmes (1950) suggests that a carbonatite fluid might be even more "primary" than suspected, as an original constituent of the mantle escaping into the crust and reacting with deep-seated crustal rocks to generate there a great variety of alkalic rocks. Strauss and Truter (1951b, p. 122), among others, favor the development of a residual fraction rich in $CaCO_3$ by differentiation of a peridotitic magma which acquired its CO_2 along the lines suggested by Holmes.

Brögger starts with an alkalic magma, but Von Eckermann and Holmes start with a carbonatic fluid which generates alkalic rocks and then makes carbonatites with the CO_2 left over. The volume requirements of $CaCO_3$ in a single volcanic district to make carbonatites alone would not be insurmountable, but that required to help generate all the intrusive and extrusive alkalic rocks as well as the carbonatites calls for some really big source of carbonate.

N. L. Bowen, a sterling magmatist in other matters, became convinced of the hydrothermal origin of the carbonatites at Fen from petrographic evidence and from the experimental work of Smyth and Adams (1923) which showed that an excessively high temperature was required for a carbonate magma. His paper (1924) found many followers in North America, largely because of the prevailing thought among most American economic geologists that carbonates are deposited from dilute hydrothermal solutions. In support of the magmatists, however, it should be kept in mind that a natural carbonatic liquid would be impure, could exist under pressure and compositional conditions at temperatures significantly lower than its melting point (1389°C.), and need not be called a magma. To throw out the possibility of a dense carbonatic liquid on the temperature argument alone might be unwarranted until many more experimental studies have been completed.

S. J. Shand has remained steadfast in his view of the origin of carbonatites as altered xenoliths, as expressed in his paper on the Palabora complex in 1931. Even in a recent discussion (Strauss and Truter, 1951a, p. 127), when confronted with evidence of an "intrusive" nature of the carbonatite, he has preferred the alternative of "mobilized dolomite" to magmatic carbonatite. The writer suspects that Shand's views strive not so much to oppose the existence of carbonatic fluids as to retain limestone assimilation as one working hypothesis for the origin of alkalic rocks. The idea of mobilization of carbonate rock under conditions of orogenic stress and elevated temperature is well established in modern petrology, and recent experiments indicate plastic flow can occur easily under the most moderate temperature and pressure. The environmental association of the carbonatites in Tertiary volcanic rocks and plugs in stable areas would not alone favor some other genesis of the carbonate, for alteration after foundering or rafting may cause carbonate rock xenoliths to look like carbonatites if the original contact relations with wall rock are destroyed. Contact relations are most critical, perhaps more so than mineral composition. The writer doubts if all the "ring dikes" can be explained as mobilized rock. If "mobilized" implies much more than alteration and purely physical readjustment we can then accept the $CaCO_3$ as mobilized instead of chemical concentration in a crystallizing silicate magma.

The many occurrences of carbonatites in East African explosive vents, agglomerate, and brecciated plugs must certainly impress many persons with the necessity for great energy such as could be produced by release of a constricted gas. In active volcanoes with alkalic affinity, a large quantity of escaping gas has been reported by Verhoogen (1948; 1939) from Nyamuragira and Rittmann (1930) from Vesuvius. The question we are faced with is whether the presence of the gas phase alone is sufficient for the deposition of $CaCO_3$ and other minerals in carbonatites. The writer suspects that in the presence of a hot aqueous solution containing dissolved CO_2 a substantial quantity of constituents could be acquired by corrosive attack of silicate rocks and transported elsewhere. With decrease in partial pressure as the ascending solution nears the surface, precipitation is inevitable as CO_2 is released. But would the same or more chemical activity occur if the ascending fluid is essentially a gas composed of CO_2, H_2O, S, F, B, etc.? Certainly gas is present in the erupting volcanoes, but was it important in the transport and deposition of the heavier elements? Most of our experimental and ob-

servational information suggest that gases under such conditions are even more active than dilute aqueous solutions and that gas transfer could contribute significantly to the formation of carbonatites as well as other rocks (*e.g.*, fenite) characteristic of these geologic environments. But what of the carbonatic liquid yielding this gas?

Source of CO_2

An immediate source of CO_2 can be provided, of course, by simple mechanics of separation from—to use King's phrase—a carbonated alkalic magma. The writer doubts, however, whether we can ever satisfactorily guess at an ultimate source without prejudging the origin of the alkalic rocks themselves. We have ample evidence of the generation of subsilicic, alkalic magma in the crust by reason of substantial volcanic piles of similar composition. Is there but one mode of origin for the alkalic magma? If so, and if it is independent of the acquisition of foreign carbonate rock, such a magma derived by differentiation of a subalkaline magma, as postulated by Bowen (1945), would normally concentrate its juvenile fugitive constituents as the differentiation proceeded. In fact, the increase in concentration of these constituents might itself aid the process, as Smyth (1913; 1927) has suggested. The continual release of juvenile constituents as a result of magma generation in geologic time was argued well by Rubey (1951; 1955). Acquisition of additional CO_2 from the crust would serve merely to add more spice to the pudding.

But if acquisition of foreign carbonate or CO_2 is prerequisite for the development of alkalic rocks, then the CO_2 may be juvenile (primary) or resurgent (recycled). The world-wide occurrence of alkalic igneous complexes in the more stable continental platform areas, as pointed out by Backlund (1932) and Polanski (1949), among others, might require some special set of conditions in tectonics, gas-phase buildup, and deep-seated magma generation. Holmes (1950) thus brought up carbonatitic fluid along fractures in the mantle. One can, however, with less difficulty calcine dolomite or limestone in the deeper part of the basement complex, or near the region of invading magma (Faust, 1949), channel the hot escaping gas along fractures, and thus provide material for chemical action within the crust. The writer's investigations in Montana have convinced him that the alkalic magma there was generated as such before it left the Precambrian basement to enter the Paleozoic and younger strata. One great difficulty of the Daly-Shand limestone syntexis hypothesis is in creating great volumes of the mafic, subsilicic, potassium-rich magma. This kind of magma is abundantly illustrated in many provinces as the principal extrusive as well as intrusive rock. It can just as easily be obtained by partial or complete fusion of deeply buried metamorphic rocks to generate a mafic alkalic magma, as suggested by Waters (1955, p. 720), and permit differentiation of this magma to yield the types seen at the surface.

If carbonatites contain mostly recycled CO_2, then most of the other minor constituents are probably recycled also and were concentrated during silicate crystallization. The source of the carbon dioxide and other minor constituents lies deep in the crust, as does the source of the alkalic magma—out of sight but not out of mind. Their origin must be linked to continental history.

Summary and Conclusions

In this review, the writer has taken the position that the term carbonatites should be restricted to those special carbonate-rich rocks in alkalic provinces that can be shown to be intrusive and formed by precipitation from hot solutions of any temperature and concentration. They represent carbonatic solutions, and further experimental inquiries may aid us in determining the physical chemistry of the solutions. Beyond the restricted Bröggerian sense, one might include any carbonate-rich dikelike, veinlike, or pluglike body in any province in order to avoid the genetic connotation that has attached itself to the terms dike, vein, or plug. The position thus taken extends Brögger's original concept of magma to include dilute or dense aqueous or gaseous solutions. Xenoliths and skarns are not carbonatites. The term is especially appropriate for those dikelike tabular, lenticular, or arcuate bodies described by many authors. The larger masses of carbonate rock within alkalic complexes or volcanic necks are likewise called carbonatites if it cannot be

established that they are xenoliths. In the absence of fossils, original sedimentary bedding structures must be clearly distinguished from the "flow structure" so characteristic of the massive carbonatites. Perhaps detailed field studies may yet reveal that both xenoliths and carbonatites occur in the same complex.

Experimental investigations at many laboratories will undoubtedly increase our knowledge of the phase relations, geologic thermometry, and conditions of formation for these interesting and complex carbonate rocks. Mineralogical studies leading to a better understanding of geochemical distribution are inevitable. A most fruitful field of inquiry is in absolute age determination by application of modern geochemical age methods in an effort to establish geochronology within a petrographic province of different alkalic districts and regional tectonics.

The carbonatites and associated alkalic rocks are proving to be important future sources of rare commodities. Deposits of rare earths, barite, phosphate, uranium, and niobium (columbium) have already been established. Intensive inquiry into all alkalic petrographic provinces is indeed warranted in the search for additional deposits. Detailed future field investigations will probably add to our list of known carbonatite localities, better define their field relations and size, and increase our future supply of some rare natural resources.

In his own field investigations on carbonatites, the writer has concluded that the CO_2 is derived by a process of concentration of residual ingredients during crystallization of the silicate minerals. At elevated temperatures and high confining pressures the residual fraction becomes increasingly richer in CO_2. Moreover, CO_2 is probably the principal fugitive ingredient in some of these freak magmas rather than, or in addition to, water. Continued crystallization yields, therefore, ever-changing mobile solutions rich in CO_2. As these hot solutions follow the pressure gradient toward the surface along intermittent fractures and conduits, the critical region is reached where CO_2 departs from the carbonatic solution as a gas and thereby provides conditions suitable for gas buildup, explosive phenomena, and precipitation of minerals. The writer considers the pressure factor more important than temperature for the rate in fall of pressure is judged to be more rapid than rate in temperature fall. The ultimate source of CO_2 in alkalic magmas is a problem apart from the formation of carbonatites.

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Short Notes

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AGE OF THE BLACK HILLS GOLD MINERALIZATION

BY J. L. KULP, W. R. ECKELMANN, P. W. GAST, AND D. S. MILLER

The times of hydrothermal mineralization in the Black Hills have been the subject of considerable interest and discussion. A great deal of this discussion has centered about the Homestake gold deposits about which there have been several detailed geologic studies. Hosted and for lead. The first specimen (Table 1) consisted of galena intimately associated with the gold quartz veins of the main mineralization cycle, while the second galena, collected at the Spokane Mine in the Keystone area, came from a lead vein which has been described as essentially

TABLE 1.—ISOTOPIC COMPOSITION OF BLACK HILLS GALENAS

Sample no. and location	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	Estimated age
K-141 (Homestake Gold Mine)*	1.00	16.39	15.72	36.33	1500–1700
	1.44(0) ± .004	23.60 ± .04	22.64 ± .04	52.32 ± .05	
BH-1 (Spokane Mine)	1.00	18.42	15.94	38.12	⩽400 m.y.
	1.36(1) ± .004	25.07 ± .04	21.69 ± .05	51.88 ± .05	

* Sample supplied by R. E. Sargent, Homestake Mining Co., Lead, S. D.

Wright (1923) suggested that all mineralization was Tertiary, while Paige (1924) and Connolly (1927) concluded that the main mineralization was Precambrian, but that some Tertiary mineralization was possible. Noble (1950) concluded that there probably was only one period of mineralization and that its age could not be determined from the available data. The Spokane Mine, about 4½ miles southeast of Keystone, represents the only significant hydrothermal mineralization in the southern Black Hills. No direct geologic evidence concerning the age of this deposit is available, but its mineralogy is similar to that of the Tertiary deposition of the northern Black Hills.

Recent isotopic and chemical analyses on several uraninites from the Bob Ingersoll pegmatite (Tilton, 1956; Eckelmann and Kulp, In press) have shown that pegmatites intruding the schists and gneisses of the southern Black Hills were formed 1620 ± 20 m.y. ago.

As part of an extensive study, two galenas from the Black Hills were isotopically analyzed conformable with the enclosing schist walls (Connolly and O'Harra, 1929). The isotopic composition for the two samples is given in Table 1.

An approximate age for the galena from the Homestake Mine has been calculated using graphs similar to those given by Geiss (1954). Depending on the parameters chosen, the age derived for the Homestake galena is 1500–1700 m.y.

The similarity of the age of the uraninite from the Bob Ingersoll Mine and the age of the galena from the Homestake deposit suggests that these two geologic events are contemporaneous. Since the common lead isotopic variations are rather insensitive to time in the post-Cambrian, an accurate age cannot be obtained for the Spokane galena. However, it is considerably younger than the Homestake sample, and its isotopic composition is not inconsistent with a Tertiary age.

It can thus be concluded that there definitely has been a period of Precambrian mineraliza-

tion in the Homestake deposit and that this mineralization is probably contemporaneous with the pegmatites of the southern Black Hills. A second period of mineralization in the Paleozoic or later has also been established.

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DISTRIBUTION AND ABUNDANCE OF CHERT AND FLINT AS RELATED TO THE Ca/Mg RATIO OF LIMESTONES

BY GEORGE V. CHILINGAR

Introduction

As pointed out by Twenhofel (1950, p. 384), it is a question whether chert and flint are more abundant in dolomitic than in calcitic limestones. Chert and flint deposits are indicative of the depth and physical-chemical environment of deposition and diagenesis. In addition, their distribution is of great importance to various industries which need pure limestones.

Each year about 324 million tons of dissolved silica is brought to the oceans; this is equivalent to 0.23 mg SiO_2/m^3 of sea water (Bruevich, 1953, p. 71). The annual supply of silica to the oceans is approximately the same as the loss to the bottom (K. O. Emery, personal communication). The maximum observed content of SiO_2 in the oceans is 26.7 mg/liter (Bruevich, 1953, p. 71), and, therefore, it would take only about 26 thousand years for the accumulation of present content of SiO_2 in the oceans, disregarding any removal. The waters of the oceans are probably undersaturated ($\cong$⅓), because the interstitial waters of the sea bottoms can contain as much as 80 mg SiO_2/liter. The SiO_2 does not really have a saturation value, however, because the saturation value depends on the ionic form, influence of other ions, and pH. In addition, the values for interstitial water are not directly comparable to those of sea water because of the differences in the nature of water.

Most of the silica in sea waters is in the monomolecular form (H_2SiO_3), and contrary to the statement of Twenhofel (1950, p. 405) only small amounts are present as colloidal silicic acid (Bruevich, 1953, p. 68). For example, according to Gololobov (1943, *in* Bruevich, 1953, p. 68) the average proportions of dissolved, colloidal, and planktonic silica in the Azov, Caspian, and Black seas are respectively 70, 18, and 12 per cent.

There are two schools of thought concerning the origin of silica in the sediments. Samoylov and Rozhkova (1925), Teodorovich (1950), and many other geologists believe that silica is derived from skeletal remains of siliceous organisms. Tarr (1926), Arkhangel'skiy (1936), and others think the silica was inorganically precipitated.

According to Vishnyakov (1953, p. 88), cherts are most common in the fine- to medium-grained, deeper-water limestones formed in the quiet parts of a basin. Vishnyakov also found that cherts are more abundant in the deep-water, foraminiferal facies than in the shallower-water, brachiopod facies. This led him to believe that in sea water rich in electrolytes silica could have been transported only in suspension. The silica transported in the form of hydrophyllic colloid is not very sensitive to electrolytes and can be additionally stabilized by protective colloids of organic origin. The action of protective colloid was demonstrated by the writer (Chilingar, 1953, p. 206) by adding a few grams of gum tragacanth to a beaker with precipitated silica gel. The gum tragacanth peptizes the silica by forming a protective cover around each particle.

According to Teodorovich (1950, p. 451), the oölitic limestones which formed in waters subjected to movements lack chert stringers and nodules. He also believes that low pH, low temperature, and rising salinity favor precipitation of silica (p. 150).

Diagenetic Chert Nodules of the Joana Limestone

Several chert nodules 1 foot in diameter from the Joana limestone member of the White Pine shale near Hamilton, Nevada, have been carefully studied. Although the border line between these nodules and the surrounding limestone is very sharp, the chemical analyses showed a definite variation in the SiO_2, $CaCO_3$, and $MgCO_3$ contents from periphery toward the center of the nodules (Table 1). These results show incomplete replacement of limestone in the peripheral area of the nodules. The increase in the Ca/Mg ratio in going from central to peripheral part of the nodule is probably indica-

tive of the selective replacement of calcium by silica; and the replacement was probably going on in the following manner:

$$H_2SiO_3 + CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{++} + 2HCO_3^- + \underline{SiO_2} + H_2O$$

The amount of silica close to nodules (0.4 to 0.6 per cent) is less than the overall average for limestone (1.1 per cent). Apparently the silica has migrated toward the nodules by diffusion from the surrounding areas, and, if the particles of silica were negatively charged, the centers of attraction were probably positively charged.

TABLE 1.—VARIATION IN CHEMICAL COMPOSITION OF DIFFERENT PARTS OF SEVERAL NODULES IN JOANA LIMESTONE, HAMILTON, NEVADA

	Average for limestone	Peripheral zone	Middle zone	Core
SiO_2 (%)	1.1	76.2	81.2	97.5
$CaCO_3$ (%)	96.0	22.1	17.1	0.51
$MgCO_3$ (%)	1.07	0.31	0.30	0.20
Ca/Mg	124.8	99.0	79.1	3.54

According to Vishnyakov (1953, p. 85), the order of replacement of organisms by silica is as follows: (1) crinoids and spicules of echinoids with monocrystalline texture, (2) prismatic layers of spirifers, and (3) Foraminifera. This order of replacement is opposite to the one found by the writer for dolomitization (Chilingar, 1956, p. 13). Vishnyakov (1953, p. 85), who also states that coarse-grained calcite is selectively replaced by silica, does not explain why the fine-grained calcite, which is more soluble than coarse-grained calcite, is not replaced first.

The writer found that the silica in nodules is mainly in the form of chalcedony with minor amounts of quartz. The degree of recrystallization in the central and peripheral portions of nodules also appears to be different; more quartz is present in the central area. Inasmuch as no skeletal remains of siliceous organisms were found in the Joana limestone nodules, the writer believes the silica in this case is probably of inorganic origin.

In homogeneous limestone outcrops the percentage of chert nodules and stringers slightly increases with increasing Ca/Mg ratio (Chilingar, 1956, p. 95). This is probably related to the fact that alkalinity favorable for the precipitation of more dolomitic limestones (Chilingar, 1956, p. 56) tends to keep the silica in solution. The fact that alkaline waters tend to keep silica in solution has been demonstrated by numerous investigators (Twenhofel, 1950, p. 399).

Bedded Cherts of the Anchor Limestone Member of the Monte Cristo Formation, Nopah Range, California

The Anchor limestone member of the Monte Cristo formation, Nopah Range, California, consists of gray limestone interbedded with brownish-weathering chert. The chert and limestone beds range from ½ to 6 inches in thickness, and the limestone-chert ratio ranges from about 4:1 at the bottom to about 1:1 at the top. The chemical composition of chert and limestone bands, based on 10 analyses, is indicated in Table 2.

TABLE 2.—CHEMICAL COMPOSITION OF CHERT AND LIMESTONE BANDS OF ANCHOR LIMESTONE, NOPAH RANGE, CALIFORNIA

	Range in chemical composition of chert bands (Per cent)	Range in chemical composition of limestone bands (Per cent)
SiO_2 (Chalcedony)	29.07–80.0	1.1–14.1
Mg	0–0.1	0.1–0.7
Ca	8.0–21.95	32.1–35.8

Inasmuch as the Ca/Mg ratio is higher in the chert bands than in the limestone bands, the writer excludes replacement as an explanation because it seems that silica selectively replaces calcium (Table 1). Probably the higher pH required for the precipitation of Mg tends to keep the silica in solution, whereas silica precipitates at lower pH. The difference in the magnesium content of chert and limestone bands, therefore, suggests a primary origin for these bedded cherts.

Conclusions

Carbonate rocks with high concentration of chert nodules, stringers, and beds usually have

high Ca/Mg ratios, and similarly with increasing Ca/Mg ratios the percentage of chert stringers and nodules increases. Apparently the high pH and high temperature, which favor the deposition of dolomitic limestones, are not favorable for the precipitation of silica. This relationship holds true, however, only where the silica that forms chert nodules and stringers was deposited contemporaneously with the enclosing rocks (which is usually the case). In places, secondary dolomitization obscures the relationship.

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University of Southern California, Los Angeles, Calif.

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